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Determination of thiodiglycol in groundwater using solid-phase extraction followed by gas chromatography with mass spectrometric detection in the selected-ion mode

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Abstract

A highly sensitive analytical procedure is described for determining thiodiglycol in groundwater. Samples are initially fortified with 3,3′-thiodipropanol (surrogate), then both species are extracted using sequential solid-phase extraction with both C_{18} and Ambersorb 572 columns. The C_{18} column, which removes extraneous groundwater components, is discarded; the Ambersorb 572 column is dried thoroughly before eluting polar components with a small volume of dichloromethane. The extract is taken to dryness using dry flowing nitrogen, and the resulting residue is derivatized using *N*-(*tert*.-butyldimethylsilyl)-*N*-methyltrifluoroacetamide and pyridine. The derivatized products are diluted to a final volume with toluene, chromatographed using a fused-silica capillary column, and detected with a quadrupole mass spectrometric detector in its selected-ion mode. Two independent, statistically unbiased, procedures were used to evaluate the detection limits for thiodiglycol; the values ranged between 4 and 16 $\mu g\ l^{-1}$ groundwater.

Keywords: Water analysis; Environmental analysis; Warfare agents; Thiodiglycol; Sulfur mustard; Thiodipropanol; Sulfur compounds

1. Introduction

Sulfur mustard [HD, *syn.* bis(2-chloroethyl)sulfide; CAS Registry No. 505-60-2] is an organosulfur blister agent that was first deployed in World War I and has been used occasionally ever since. It was manufactured by several agencies during World War II, including the US Army Rocky Mountain Arsenal between December 1942 and May 1943 [1]. Sites such as the Rocky Mountain Arsenal are currently being remediated and converted to non-military uses. In order to ensure that the final site contains soil and groundwater with contaminant levels below those recommended by the regulatory agencies, rigorously tested analytical methods must be available that will (a) demonstrate the presence or absence of HD at regulatory levels in soil or groundwater samples, (b) be readily implemented by most commercial analytical laboratories, (c) be rapid and convenient to use, and (d) generate minimal final quantities of chemically hazardous waste. The determination of traces of HD and its decomposition products is crucial to support efforts in the remediation of contaminated sites at many military installa-

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tions and the verification of arms-control agreements in compliance with the Chemical Weapons Convention.

The primary degredation pathway of stored or buried HD is hydrolysis [2]. Although HD is rapidly hydrolyzed (half-life of 8.5 min at 25°C [3]), its rate is limited by the slow rate of dissolution. The hydrolysis mechanism is complex and, depending upon the availability of water, occurs by two routes, both of which lead to the initial formation of thiodiglycol (TDG, *syn*. 2,2′-thiodiethanol; CAS Registry No. 111-48-8) and hydrochloric acid. Hence, the presence of TDG in a groundwater sample is an excellent indicator of legacy HD manufacture or storage. The current target reporting limit (TRL) set by the US Army Rocky Mountain Arsenal for TDG in groundwater [4] is 5 $\mu g\ l^{-1}$.

Many analytical procedures for TDG take advantage of its high solubility in water and employ high performance liquid chromatography (HPLC). However, all of these procedures either exhibit insufficient sensitivity or selectivity, or require instrumentation that is currently unavailable in most commercial analytical service laboratories. Raghuveeran et al. [5] described an HPLC-based method with UV detection at 200 nm that clearly exhibited insufficient selectivity and sensitivity for the present purpose. Substituting a simple UV detector with either a sulfur chemiluminescence detector [6] or derivatization with sodium-*N*-chlorobenzenesulfonamide followed by UV detection [7] improves both sensitivity and selectivity, but requires equipment that is unavailable in most analytical service laboratories.

Hooijschuur et al. [8,9] and Kientz et al. [10] described the successful quantitation of TDG using liquid chromatographic microcolumns employing large-volume injections and peak compression coupled with sulfur flame photometric detection. Bossle et al. [11] and Clark [12] described the separation of TDG and its sulfoxide and sulfone analogs in environmental waters using ion-exclusion HPLC with subsequent detection using UV and/or pulsed amperometric detectors. Cheicante et al. [13] investigated the separation and detection of 27 chemical weapons' degradation products, including TDG, with capillary electrophoresis and UV detection. Liquid chromatographic microcolumns have also been coupled to mass spectrometric detectors in a variety of operating modes, including electrospray [14,15] and atmospheric pressure chemical ionization [16,17]. All of these procedures demonstrate the necessary sensitivity and selectivity, but all of them also require analytical instrumentation that is unavailable in most commercial analytical service laboratories.

Gas chromatography with a form of mass spectrometric detection is an attractive alternative to the various HPLC-based methods described, in that most commercial analytical laboratories possess the required equipment. The desired sensitivity and selectivity should certainly be achievable. Because gas chromatographic peaks for TDG usually exhibit considerable tailing and asymmetry [18], GC-based procedures typically include a derivatization step, both to improve the peak shape and improve the detection limit of the analyte.

Several successful combinations of derivatization and mass spectrometric detection have been reported. Black and Read [19] converted the urinary metabolites of sulfur mustard, including TDG, to their corresponding bis(pentafluorobenzoate) derivatives prior to gas chromatography–tandem mass spectrometry (GC–MS–MS) or electron-capture negative ion chemical ionization mass spectrometry in the selected-ion monitoring mode [20]. TDG present in the urine of exposed rats or guinea pigs has been derivatized with heptafluorobutyric anhydride prior to gas chromatography with mass spectrometric detection, with excellent results [21,22]. Rohrbaugh [23], D'Agostino and Provost [24], and Schoene et al. [25] obtained useful results with the readily formed silyl esters. These authors employed electron ionization and ammonia or methane chemical ionization processes in the final detection and quantitation of the derivatized products. Rohrbaugh [23], in particular, employed derivatization with bis-(trimethylsilyl)trifluoroacetamide (BSTFA) to form trimethylsilyl esters that were examined in both the electron impact (El) and chemical ionization (CI) mode using methane as the reagent gas. His mass spectrum displayed from the El mode showed no strong diagnostic mass-to-charge ratios (m/z), while that from the CI mode exhibited two significant characteristic ions (intensity $>75\%$ of the base peak) that would be excellent for quantitation. Wils et al. [26] described a unique procedure for quantitating thiodiglycol in urine in which the analyte was

converted to HD with concentrated hydrochloric acid prior to headspace analysis. This method was not investigated further because ''live'' sulfur mustard chemical agent is formed, thereby introducing possible exposure to chemical workers.

While not all commercial service analytical laboratories can implement chemical ionization easily, all are capable of employing selected-ion monitoring (SIM) [27] provided that the derivatized products exhibit at least one ''strong'' characteristic m/z peak. Additional devices, such as surface acoustic wave (SAW) [28] and ion trap mass spectrometric (ITMS) [29] detectors, have been proposed for the detection of either TDG or HD.

Aliquots of either groundwater or urine are typically taken to dryness using dry flowing nitrogen prior to any of the derivatization procedures for TDG described above. This drying step introduces a potentially severe limitation into any GC–MS-based method. Only small aliquots may be employed, due to the difficulty in removing the aqueous matrix. For that reason, some investigators have considered the possibility of using carbonaceous sorbents to remove TDG from aqueous samples. Sng and Ng [30] described the solid-phase microextraction of six chemical warfare agent degradation products, including TDG, from aqueous samples using a Carboxen–polydimethylsiloxane-coated fiber. The collected analytes were exposed ''on fiber'' to the headspace of *N*-(*tert*.-butyldimethylsilyl)-*N*-methyltrifluoroacetamide (MTBSTFA), a powerful silylating reagent, prior to thermal desorption into the inlet of a gas chromatograph followed by mass selective detection. These authors noted, however, that while the procedure was modestly successful for ethyl-2-hydroxyethyl sulfide, it was only weakly successful for TDG.

Leong et al. [31] studied the adsorptive capacity of four carbonaceous sorbents, viz., Ambersorb XEN-563, Carbochem LQ830, Carbochem LQ1000, and Morganite FY5, towards four organosulfur compounds (TDG, ethyl 2-hydoxyethylsulfide, 1,4-thioxane, and ethyl vinylsulfide) in water. All four adsorbents demonstrated decreasing adsorptive capacity with increasing polarity of the adsorbates. Of these sorbents, Morganite FY5 and Ambersorb XEN-563 exhibited the highest adsorptive capacity for the selected adsorbates. A manufacturer's note from Supelco (Bellefonte, PA, USA) [32] suggested that Ambersorb XEN-563 might not have been the best choice for a polar adsorbate such as TDG because it exhibited the highest ''hydrophobicity ranking'' of five Ambersorb sorbents sold at the time. By contrast, Ambersorb 572 exhibited the lowest ''hydrophobicity ranking'' (conversely, the highest ranking for hydrophilic compounds), and would therefore be a better choice for extracting polar analytes such as TDG from aqueous matrices.

The present work expands the work of Leong et al. [31] to provide a viable method for quantitating TDG in groundwater at low $\mu g\ l^{-1}$ concentrations. Aliquots (100 ml) of groundwater are fortified with 3,3′-thiodipropanol (TDP, surrogate), then passed through a tandem solid-phase extraction system consisting of a C_{18} reversed-phase cartridge (removes groundwater contaminants) and a hand-packed Ambersorb 572 column. The latter is dried thoroughly; materials collected are eluted with a small volume of dichloromethane, which is subsequently taken to dryness in the presence of pyridine. Pyridine acts as a ''keeper'', and helps retain TDG during the concentration step. Fresh pyridine is added to the residue, which is derivatized with silylating reagent [MTBSTFA with 1% *tert*.-butyldimethylchlorosilane (TBDMS–Cl) catalyst] [33] and diluted with toluene. Quantitation of TDG and TDP is performed using GC–MS in the SIM mode. The detection limits and recoveries for both derivatized species were rigorously determined using protocols mandated by both the US Army Rocky Mountain Arsenal and the US Environmental Protection Agency. The final chemical waste produced that required disposal did not exceed 1 ml per sample.

2. Experimental

2.1. Chemicals

TDG, 3,3′-thiodipropanol (TDP; CAS Registry No. 10595-09-02), and MTBSTFA (CAS Registry No. 77377-52-7) with 1% TBDMS–Cl (CAS Registry No. 18162-48-6) were purchased from Aldrich (Milwaukee, WI, USA) at 99+% purity. Silylation-grade pyridine (CAS Registry No. 110-86-1) was obtained from Sigma (St. Louis, MO, USA). Toluene (CAS Registry No. 108-88-3), HPLC-grade water,

acetonitrile (CAS Registry No. 75-05-8), and dichloromethane (CAS Registry No. 75-09-2), of HPLC grade or better purity, were purchased from J.T. Baker (Phillipsburg, NJ, USA) or Allied Signal, Burdick & Jackson (Muskegon, MI, USA). Reagent-grade sodium chloride and anhydrous sodium sulfate were procured from Fisher Scientific (Fair Lawn, NJ, USA) and EM Scientific (Gibbstown, NJ, USA). All chemicals were used without further purification.

2.2. Sorbents and sample-preparation equipment

Ambersorb 563 (20–50 mesh, 550 m^2 g^{-1} specific surface area; part No. 10430-U) and Ambersorb 572 (20–50 mesh, 1100 m^2 g^{-1}; part No. 10432-U) were purchased from Supelco (Bellefonte, PA, USA). These sorbents were packed as required into empty 6-ml capacity surgical polypropylene columns (J.T. Baker; part No. 7121-06) with customary 20-μm porosity Teflon frits. Columns (6-ml) containing 500 mg of Envi-Carb (graphitized nonporous carbon, 100 m^2 g^{-1}, 120–400 mesh; part No. 57094) were obtained from Supelco. Disposable 6-ml columns packed with 500 mg of Bakerbond SPE octadecyl C_{18} (part No. 7020-06) and 75-ml empty surgical polypropylene sample reservoirs (part No. 7120-03) were purchased from J.T. Baker.

All groundwater samples were extracted using a 12-position solid-phase extraction manifold with Teflon valves and needles and a vacuum was applied from the stainless-steel top, rather than the side, of the glass chamber (Burdick & Jackson; part No. 9400). Dichloromethane extracts were collected and derivatized (as described below) in 8-ml shell vials (part No. 224804; Wheaton, Millville, NJ, USA) and sealed using 15-425 plastic black caps with open tops (part No. 240529; Wheaton) and PTFE-faced silicone rubber septa (part No. 73816-15; Kimble-Kontes, Vineland, NJ, USA). Derivatised and diluted residue was ultimately transferred to 2-ml amber silanized automatic sampler vials (part No. C4000-2W) bearing hole caps with triple-layered red Tefl-on-white silicone rubber-red Teflon septa (part No. C4000-53R, -53G, 53B, or -53Y), all products of National Scientific (Lawrenceville, GA, USA).

Two multi-block heaters (part No. 2090; Lab-Line Instruments, Melrose Park, IL, USA) were used during sample preparation. One, which was used strictly for extract concentration, was positioned underneath a nine-port Reacti-Vap Evaporator (part No. 18780; Pierce, Rockford, IL, USA) attached to a nitrogen cylinder (99.999% purity). The usual cast aluminum heating block was turned over, enabling shell vials to stand under the vanes of the evaporator in full view of the analyst. The block temperature was maintained at 45°C. The second, which was used strictly for derivatization, was maintained at 105°C and employed a heating block that had been drilled for 12/13-mm-diameter vessels (i.e., 8-ml shell vials) and a thermometer.

2.3. Preparation of ''model'' groundwater

Dissolve 1.48 g of anhydrous sodium sulfate and 1.65 g of sodium chloride in 1-l of HPLC-grade water. A 100-ml aliquot is subsequently diluted to a final volume of 1 l with HPLC-grade water to form ''model'' groundwater; the concentrations of both chloride and sulfate are 100 mg^{-1} l each [34].

2.4. Stock and spiking solutions

TDG and TDP (100-mg amounts) were weighed into separate 10-ml volumetric flasks and diluted to the mark with acetonitrile, to form ''master'' stock solutions of each compound (10 mg ml^{-1}). These, in turn, were diluted ten-fold and 100-fold with acetonitrile, as required. ''Working calibration solutions'' contained both TDG and TDP at either 1 or 0.1 mg ml^{-1}, while the ''working spike solutions'' contained a single analyte at these same concentrations. These solutions display an indefinite shelf life (minimum 60 days) and may be stored either at room temperature or at 4°C.

2.5. Instrumentation

A Hewlett-Packard Model 5890 Series II gas chromatograph interfaced to a Hewlett-Packard Model 7673 automatic sampler and Hewlett-Packard Model 5989A quadrupole mass spectrometer was used for all measurements. The injector was equipped with a double-gooseneck injector sleeve (4 mm I.D.; part No. 20786; Restek, Bellefonte, PA, USA). The fused-silica gas chromatographic column was an HP-5MS Ultra Low Bleed (5% diphenyl–

95% dimethylsiloxane), 30 m×0.25 mm I.D., 0.25 μm film thickness. The head pressure of the carrier gas (helium, 99.99% purity) was 54 kPa (7.8 p.s.i.). The automatic sampler syringe was flushed twice each with methanol and toluene before injecting 1 μl of sample into the gas chromatograph.

2.6. Instrument's operating parameters

The injector, detector, and mass transfer line temperatures for the gas chromatograph were 250, 280, and 280°C, respectively. The column oven temperature was increased linearly from 100°C (hold for 3 min) to 270°C (hold for 1 min) at 10°C min^{-1}.

The mass spectrometer operated at source and quadrupole temperatures of 200 and 100°C, respectively, and a source manifold pressure of less than $8 \cdot 10^{-6}$ Torr (1 Torr=133.322 Pa). The ionization mode was electron impact (70 eV), with an electron multiplier voltage of 50 V above the ''tune'' voltage. The ''solvent delay'', or the time after the start of a given analysis until the mass spectrometer was turned on, was 14 min.

The GC–MS system was operated in its SIM mode, in which the m/z monitored for TDG was 293, while those monitored for TDP were 321 and 363. The selected ions for TDG were scanned between 14 and 16.5 min, while those for TDP were scanned between 16.5 and 19 min. The ''dwell times'', or time spent monitoring a given m/z value, for 293, 321, and 363 were 400, 400, and 100 ms, respectively. The ''low mass resolution'' feature was ''on'', allowing a mass peak width of 0.9 amu (atomic mass units). The increased peak width (normally 0.5 amu) increased sensitivity with little loss in specificity.

2.7. Calibration procedure

An aliquot of the desired ''master calibrating'' solution (normally 10 to 100 μl) was combined with 100 μl each of pyridine and MTBSTFA with catalyst in a 2-ml silanized automatic sampler vial. The vial was capped and heated to 105°C for 1 h, then cooled to room temperature. The contents of the vial were diluted to 1 ml with toluene, then analyzed for TDG and TDP by GC–MS-SIM according to the parameters noted in Sections 2.5 and 2.6. If reanalysis of the extracts is either expected or desired, the vials may be recapped and stored at 4°C for at least seven days. Daily calibration of the mass spectrometer with derivatized standards is recommended.

2.8. Optimized groundwater analysis procedure

Portions (100 ml) of model groundwater were fortified to a desired concentration of TDG (2–100 ng TDG ml^{-1}) using one of the two ''master spiking'' solutions (2–100 μl) for TDG. In addition, each groundwater sample was fortified with 25 μl of 0.1 mg ml^{-1} (μg μl^{-1}) surrogate TDP, yielding a final concentration of 25 μg TDP l^{-1}.

The solid-phase extraction column train was prepared as follows: the C_{18} ''guard'' column was conditioned with two column volumes each of methanol and HPLC-grade water, while the ''extraction column'' (100 mg of Ambersorb 572) was conditioned with a single column volume of methanol and two column volumes of HPLC-grade water. Once the column-conditioning process has begun, neither the C_{18} nor the Ambersorb 572 column should be allowed to go dry. The solid-phase extraction column train consists of (a) a 75-ml reservoir, (b) a C_{18} ''guard'' column filled with water, and (c) an Ambersorb 572 extraction column filled with water, all connected using the hardware supplied with the reservoirs. The completed train is then mounted on the solid-phase extraction (SPE) manifold. The fortified groundwater sample is added to the reservoir, and liquid flow is adjusted to a flow of 2–3 ml min^{-1}, with a vacuum applied, as required. (Note that some groundwater samples may contain an excessive quantity of particle fines that will clog the ''guard column'' rapidly. In that case, ''off-line'' filtration of the fortified sample may be required prior to SPE). After the entire 100 ml sample has passed through the Ambersorb 572 column, the train is disassembled and the Ambersorb 572 column is dried under full vacuum for at least 1 h.

Materials collected on the Ambersorb 572 column are eluted, slowly if possible, into an 8-ml shell vial using three 3-ml portions of dichloromethane (typically, 8 ml of dichloromethane extract are recovered). A 100-μl aliquot of pyridine is added to the extract as a ''keeper'', and the resulting solution is taken to dryness both by warming the bottom of the

shell vial (to 45°C) and by using dry flowing nitrogen. The resulting residue is derivatized in the 8-ml shell vial at 105°C for 1 h with 100 μl each of additional pyridine and MTBSTFA with catalyst. After the derivatized mixture has cooled, it is diluted to a final volume of 1 ml with 800 μl of toluene, transferred to a 2-ml automatic sampler vial, and analyzed for TDG and TDP by GC–MS-SIM using the parameters described in Sections 2.5 and 2.6. If reanalysis is either expected or desired, the vials may be recapped and stored at 4°C for at least seven days.

2.9. Calculations

The measured integrated peak area for either TDG or TDP is calculated using the ''integrate'' function of the HP 5989A mass spectrometer data system. The peak areas from the derivatized standards were fit to a quadratic calibration curve of the form $C = aA^2 + bA + c$, where C is the concentration of analyte in the extract, in μg ml^{-1}, A is the measured peak area, and a, b, and c are regression constants, all of which should be considered statistically significant. The extract concentration was later corrected in the usual manner for the groundwater sample volume, i.e., 100 ml.

3. Results and discussion

3.1. Optimization of the sample preparation conditions

Our method for the determination of TDG in groundwater arose from our ongoing work to determine several organic acids and TDG in the same matrix. To this end, the most promising initial choices included the solid-phase microextraction (SPME) procedure described by Sng and Ng [30] and a small-scale liquid–liquid extraction method detailed in Tomkins [35]. The SPME procedure, which featured a Carboxen–poly(dimethylsiloxane) (PDMS) fiber, reportedly could extract a variety of analytes, including methylphosphonic and ethyl methylphosphonic acids and TDG, from aqueous samples that had been saturated with salt and adjusted to a pH<1. The fiber would then be exposed to the headspace of MTBSTFA, and the derivatized products analyzed using a gas chromatograph with ion trap mass spectrometric detection. We were unable to observe any derivatized products when this procedure was employed using a gas chromatograph with flame photometric detection (sulfur- or phosphorus-selective modes). We suggest, but cannot prove, the following explanation: the desired extraction of TDG using the Carboxen–PDMS-coated fiber probably did take place. However, the derivatized products never formed because the MTBSTFA vapors preferentially reacted with water retained in the fiber, rather than the desired analytes. For that reason, no products were ever observed in the subsequent thermal desorption followed by gas chromatographic analysis.

The liquid–liquid extraction method featured partitioning of the analytes from water (salt added and pH<1) into ethyl acetate. While such a procedure was modestly successful for carboxylic acids such as thiodiglycolic acid, whose recovery was approximately 40%, it was ineffective for TDG, whose recovery did not exceed 20% at a test concentration range of 20–120 μg ml^{-1}. The recovery was reduced to <1% when dichloromethane was substituted for ethyl acetate. TDG was clearly so soluble in water that traditional partitioning into an organic solvent would not yield a successful method. For these reasons, both procedures were set aside.

An alternative approach involved the adsorption of TDG onto a carbonaceous sorbent, with subsequent elution and analysis. Several sorbents were evaluated, i.e., Ambersorb 563, Ambersorb 572, and Envi-Carb. Ambersorb 572 was an attractive choice because it has been used successfully for the determination of other, small, water-miscible analytes, such as *N*-nitrosodimethylamine, in groundwater [36]. Envi-Carb is available commercially in small prepacked columns and would be convenient for routine analyses. Small columns packed with 500 ml of each sorbent were challenged with 100 ml model groundwater samples fortified to 20–50 μg TDG mL^{-1}. The analyte was eluted with a variety of solvents, including dichloromethane, ethyl acetate, methanol, and acetone. The nominal eluting condition was taken to dryness and derivatized with MTBSTFA, as described below.

It became clear that passing the sample through Ambersorb 572 and eluting TDG with dichlorome-

thane was the preferred choice of sorbent and eluting solvent. Ambersorb 563 was less successful than Ambersorb 572, while the Envi-Carb sorbent never retained TDG at all. Even with an optimized sorbent and desorbing solvent, the recoveries of TDG were both low and inconsistent. Subsequent experiments demonstrated that the lengthy concentration periods using dry flowing nitrogen, often more than 1 h, were slowly and irreproducibly volatilizing trace quantities of TDG, a compound normally considered ''nonvolatile''. By adding a small quantity (100 μl) of pyridine as a ''keeper'' and warming the bottom of the shell vial slightly (to 45°C), the sample concentration time was reduced to approximately 30–45 min, while the analyte recovery was increased to approximately 40% of test concentrations, ranging between 0.25 and 2 μg TDG ml^{-1}. We believe, but cannot prove, that the effectiveness of Ambersorb 572 in this method is related to its specific surface area, which, at 1100 m^2 g^{-1}, is the highest of the three sorbents evaluated.

The use of a carbonaceous adsorbent presented several additional challenges and considerations. First, such a sorbent is nonselective and will retain any analyte present in an authentic contaminated groundwater sample. Having all of these materials present in the final extract would provide an excessive and unwanted level of interferences, even for the most selective detectors. For that reason, a guard column was placed in tandem and ahead of the Ambersorb 572 column. The initial choice for the guard column was a 500-mg C_{18} octadecyl SPE column, which would be capable of retaining modest quantities of nonpolar interferences. Other guard columns might be more appropriate, depending upon further characterization of the interferences. Second, it is very difficult to elute the desired analytes quantitatively from an adsorption column with a small volume of organic solvent, although that is commonly done with a reversed-phase column. For example, when we attempted to elute TDG from a 500-mg Ambersorb 572 cartridge (test conditions, 0.25–2 μg TDG ml^{-1}; 100 ml sample) using three 3-ml aliquots of dichloromethane, significant quantities (up to 25% of the expected mass) of TDG were observed in the combined second and third aliquots.

Two approaches to improve the overall recovery and convenience were investigated. First, an alternative and more powerful eluting solvent was considered. This approach was immediately set aside because we had found no common organic solvent that was more effective for stripping TDG from Ambersorb 572 than dichloromethane. Second, reducing the bed mass would prevent TDG from migrating further into the bulk sorbent upon elution and possibly becoming re-adsorbed. For that reason, adsorption columns containing 500, 200, and 100 mg of Ambersorb 572 were evaluated. When each of these was challenged with a 100-ml model groundwater sample containing 0.25–2 μg TDG and TDP ml^{-1}, the recoveries observed in the initial 3-ml dichloromethane extract were similar, and ranged between 25 and 40%, regardless of the bed mass. Based on these data, we hypothesize that the adsorption of TDG and TDP on Ambersorb 572 is basically a surface phenomenon, occurring on the very top of the adsorption column. As long as the expected concentration of TDG is at trace-level and the capacity of the surface sorbent is not exceeded, the rest of the bed mass is extraneous and, in fact, inhibits quantitative recovery of analyte. For that reason, further work focused on Ambersorb 572 columns employing a 100-mg bed mass. Three 3-ml column washes with dichloromethane were employed to ensure that the sorbent was thoroughly exposed to solvent while simultaneously allowing a high ratio of eluting solvent to sorbent bed volumes. At the same time, further significant improvements in overall recovery are not expected unless advanced instrumentation featuring extraction under elevated temperature and pressure conditions (pressurized liquid extraction) is employed.

3.2. Considerations when using MTBSTFA as the derivatizing reagent for TDG

Because most commercial service analytical laboratories would possess GC–MS capabilities, the current method emphasizes derivatization of TDG with a reagent that would convert the analyte into a stable and volatile species that is amenable to highly selective and sensitive selective ion monitoring. Of the reagents available, MTBSTFA was particularly attractive, for several reasons. First, it produces neutral, volatile by-products. Second, the resulting silylated ethers are approximately 10^4 times more

stable to hydrolysis than the corresponding simple trimethylsilyl ethers. Third, the derivatizing power of MTBSTFA may be increased by the addition of 1% *tert*.-butyldimethylchlorosilane as a catalyst. Finally, analytes derivatized with MTBSTFA produce a simple, readily predicted, mass spectrum. The characteristic m/z values for any species derivatized with this reagent include (a) the molecular ion, M^+, (b) the m/z value of $(M-15)^+$, and (c) the m/z value $(M-57)^+$. The molecular ion is almost never seen; the $(M-15)^+$ ion represents loss of a methyl group and is diagnostic, but frequently it is of low intensity or absent. The $(M-57)^+$ ion represents loss of a tertiary butyl group, and is both diagnostic and of medium to high intensity. Figs. 1 and 2 show the mass spectra of both derivatized TDG and TDP and the fragmentation pathway. The m/z values chosen, one for TDG and two for TDP, exhibited the greatest available selectivity for both derivatized species. Fig. 3 shows selected-ion chromatograms for three groundwater samples fortified to different TDG concentrations. A constant mass of the candidate surrogate, TDP, was added to each portion of groundwater.

In spite of the obvious advantages, there are additional considerations when using MTBSTFA. Because water, not the analytes, will preferentially react with MTBSTFA, it is important that the Ambersorb 572 bed be completely dry prior to dichloromethane elution. The recommended drying time for the Ambersorb 572 bed is at least 1 h. In

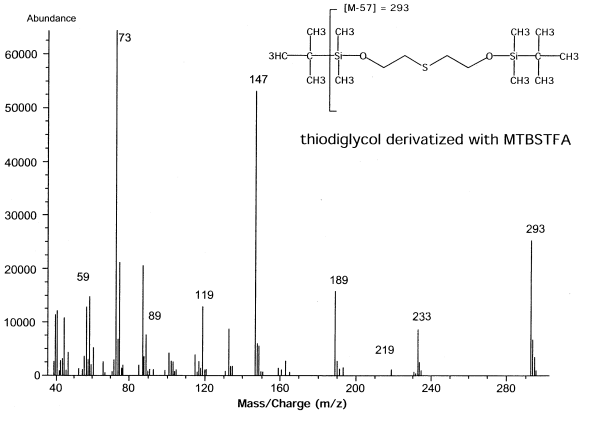

Fig. 1. Mass spectrum of derivatized thiodiglycol (TDG) showing the expected fragmentation pathway and characteristic ions.

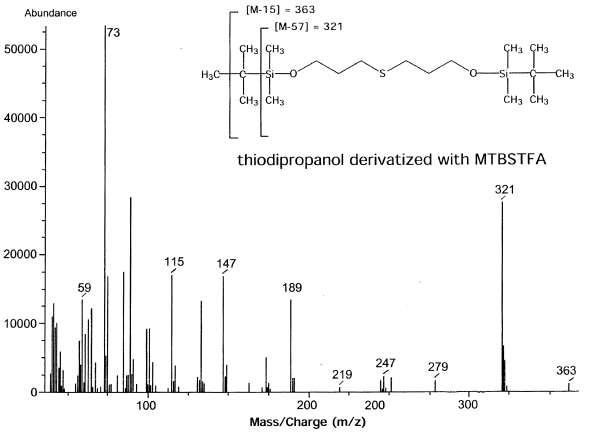

Fig. 2. Mass spectrum of derivatized thiodipropanol (TDP) showing the expected fragmentation pathway and characteristic ions.

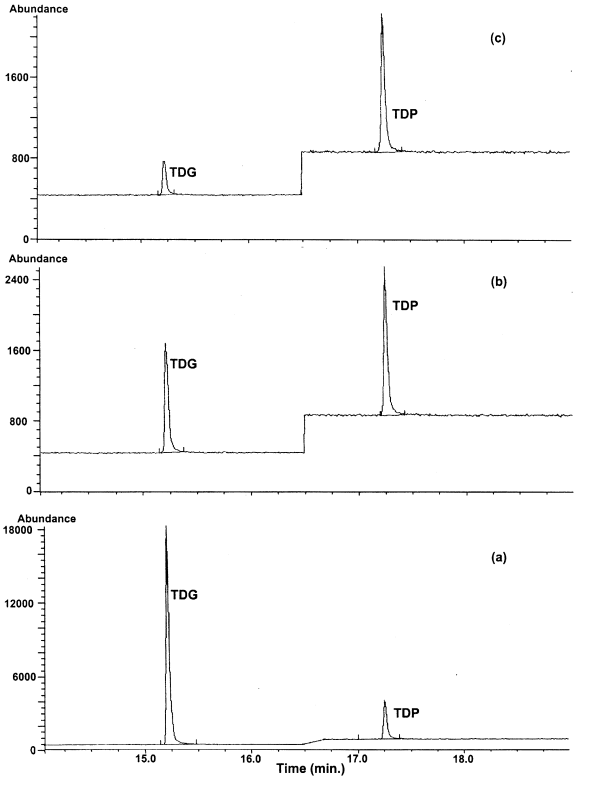

Fig. 3. Selected ion chromatograms for three groundwater samples containing (a) 25 μg TDG l^{-1}, (b) 5 μg TDG l^{-1}, and (c) 2.5 μg TDG l^{-1}. All samples also contained 25 μg TDP l^{-1} as the surrogate.

addition, it is important that both hydroxyl groups present on either TDG or TDP be derivatized. Insufficient reaction time or temperature produces both a singly derivatized species, whose presence reduces the apparent recovery of analyte, as well as the doubly derivatized entity. For that reason, both a derivatization time (1 h) and temperature (105°C) higher than normal for such reactions is recommended [18]. Derivatized standards or extracts are reasonably stable to hydrolysis. They may be stored at 4°C and re-analyzed reliably within seven days, as needed.

Previous work describing the determination of sodium fluoroacetate in soil samples noted the presence of many interfering gas chromatographic peaks in the analytical blank when shell vials and solid caps containing a fixed Teflon liner were employed [35]. These peaks were largely eliminated when hole caps with removable Teflon-faced rubber septa replaced the solid caps. We suggest that the adhesive used in the solid caps was responsible for the excessive blank, and that removing the adhesive dramatically reduced the blank. For that reason, hole caps equipped with Teflon-faced rubber septa were employed in the present work.

The miscibility of both TDG and TDP in water dictated that a polar solvent be used to prepare the ''master spiking'' and ''master calibrating'' solutions. Obvious choices, such as water, methanol, ethanol, and propanol, were eliminated because they would effectively compete with the analytes for MTBSTFA reagent. For that reason, the aprotic polar solvent acetonitrile was used in the preparation of the aforementioned solutions; few other options were readily available. The work of Purdon et al. [37], however, suggested that acetonitrile would be an improper final diluent for the derivatized products. These authors noted that on-column injection of tributyldimethylsilane derivatives in a polar solvent (e.g., acetonitrile) on a non-polar gas chromatographic column (e.g., DB-5 or HP-MS5) frequently produced very severe peak-splitting unless the injection was effected rapidly. This problem could be largely alleviated by performing the final dilution with a nonpolar solvent such as benzene or, even better, toluene. For that reason, all derivatized standards or extract residues were ultimately diluted with toluene prior to GC–MS-SIM analysis.

3.3. Method evaluation and determination of the method reporting limit and method detection limit for TDG and TDP

The performance of the proposed method was evaluated using two statistically unbiased protocols, viz., those of the US Army Rocky Mountain Arsenal [38] and the US Environmental Protection Agency [39], to determine the method reporting limit (MRL) and the method detection limit (MDL), respectively. The former is equivalent to determining a ''found'' concentration so that both the false-positive and false-negative errors are 5%, as discussed in Hubaux and Vos [40] and Grant et al. [41]. By contrast, the latter is the minimum concentration that can be measured and reported with 99% confidence that the analyte concentration is greater than zero [39].

The MRL was evaluated using a procedure established by the US Army [38] and discussed in detail elsewhere [42]. Briefly, 100 ml portions of model groundwater were fortified to 2.5–100 μg TDG l^{-1}, or 0.5 to 20 times the target reporting limit (TRL) of 5 μg l^{-1}. Each test sample was also fortified with 25 μg l^{-1} TDP, which served as a candidate surrogate. Samples were spiked, extracted, derivatized, and analyzed as described above, and the resulting model groundwater concentrations were calculated using calibration data obtained on each of two method certification days. The MRL values were calculated using the current version of software recommended by the Program Manager for Rocky Mountain Arsenal [43]. Candidate analytical methods employing GC–MS-SIM are considered to be ''self-confirming'', in that the identity of a given compound is established using both its retention time and mass spectrum or selected ions within. No independent confirmatory method was required. The spiked (''true'') and analyzed (''found'') concentrations for TDG are presented in Table 1. The slope of the calculated linear regression line representing the relationship between the ''found'' and ''true'' values may be taken as a measure of analyte recovery. The calculated MRL value for TDG was 16.2 μg l^{-1}, with a corresponding recovery of 38%.

MDL values were calculated for both TDG and TDP, the proposed surrogate, as described in Ref. [38]. A single set of nine 100-ml model groundwater samples (seven required) were independently for-

Table 1
Comparison of ''found'' vs. ''true'' concentrations for TDG using the GC–MS-SIM method in method reporting limit (MRL) certification samples

''True'' TDG concentration ($\mu g\ l^{-1}$)	''Found'' TDG concentrations ($\mu g\ l^{-1}$)	
	Day 1	Day 2
0.0	0.78	0.72
2.5	1.0	1.1
5.0	1.7	1.8
10	3.5	2.6
25	12.5	7.0
50	22.6	16.8
100	40.9	34.1
Method reporting limit (MRL) ($\mu g\ l^{-1}$)	16.2	
Estimated recovery (%)	38	

tified to 25 $\mu g\ l^{-1}$ in each of TDG (five times the TRL) and TDP, then processed as described above. The resulting calculated concentrations and sample standard deviation for each analyte are presented in Table 2. The latter value was multiplied by the appropriate value of the Student's t distribution, 2.896, representing 99% confidence and $(n-1)$ degrees of freedom (here, 8), where n is the number of data values available. The resulting values are the MDLs; these are 3.5 and 1.2 $\mu g\ l^{-1}$ for TDG and TDP, respectively. The average recoveries for TDG and TDP, obtained from the data shown in Table 2, are 23 and 17%, respectively, and reflect the difficulty in extracting these water-miscible species from a groundwater matrix. However, the recoveries are clearly consistent and reproducible. Similar recoveries were reported for the determination of *N*-nitrosodimethylamine, which is also a small, highly polar, water-miscible analyte, from aqueous samples using Ambersorb 572 as the extraction sorbent [44,45]. The extraction and derivatization behavior of TDP tracks that of TDG closely, and is therefore an acceptable surrogate compound.

Table 2
Determination of the method detection limit (MDL) for TDG and TDP using the GC–MS-SIM method[a]

Sample number	Measured TDG ($\mu g\ l^{-1}$)	Measured TDP ($\mu g\ l^{-1}$)
1	4.40	3.62
2	4.78	3.76
3	4.98	4.00
4	5.48	4.01
5	5.54	4.05
6	5.94	4.18
7	5.96	4.33
8	7.15	4.75
9	8.31	4.91
Average	5.84	4.17
Sample standard deviation	1.22	0.43
Student's t table value	2.896	2.896
MDL ($\mu g\ l^{-1}$)	3.5	1.2
Recovery (%)	23	17

[a] ''True'' concentration is 25 $\mu g\ l^{-1}$.

4. Conclusions

Thiodiglycol (TDG), a major hydrolysis product of sulfur mustard, may be extracted from groundwater samples using two solid-phase extraction columns in tandem. The reversed-phase C_{18} ''guard column'' removes extraneous interfering materials from the groundwater sample, while the column containing Ambersorb 572, a synthetic carbonaceous sorbent, extracts TDG. The Ambersorb 572 column is dried and eluted with dichloromethane. After the resulting extract is taken to dryness, it is derivatized with MTBSTFA, diluted with toluene, and analyzed by GC–MS-SIM. The detection limits for this procedure, which were calculated using two independent, statistically unbiased, procedures, ranged between 3.5 and 16 μg TDG l^{-1} groundwater. Thiodipropanol (TDP) exhibited an extraction behavior and detection limit (1.2 μg TDP l^{-1}) similar to that of TDG, and was considered to be an acceptable surrogate compound. The method recovery for both analytes is modest, ranging between 20 and 40%, and reflects the difficulty in extracting water-miscible analytes from a groundwater sample.

The typical sampling rate for the proposed method is approximately twelve to sixteen groundwater samples per 8-h working day. Calibration standards may be prepared concurrently with the groundwater extracts and should also be analyzed daily. It is strongly recommended that all sample preparation be performed during an 8-h shift, and that all subsequent GC–MS-SIM determinations be performed

independently using an instrument equipped with an automated sampler.

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