

Measurement of Fuel Oxygenates in Tap Water Using Solid-Phase Microextraction Gas Chromatography–Mass Spectrometry*

Frederick L. Cardinali[†], Benjamin C. Blount, Rachael Schmidt, and John Morrow

Division of Laboratory Sciences, National Center for Environmental Health, Centers for Disease Control and Prevention, Atlanta, GA 30341

Abstract

The presence of alkyl ether fuel oxygenates in drinking water supplies has raised public health concerns because of possible adverse health effects from chronic exposure to these compounds. To enable large exposure studies exploring possible relationships between chronic exposure to alkyl ether fuel oxygenates and health effects, we developed an improved analytical method, using headspace solid-phase microextraction coupled with capillary gas chromatography and mass spectrometry. This method quantifies trace levels of methyl tertiary-butyl ether, ethyl tertiary-butyl ether, di-isopropyl ether, and tertiary-amyl methyl ether in tap water. The method achieves detection limits of less than 0.025 µg/L for all analytes and linear ranges of three orders of magnitude in the measurement of the alkyl ether fuel oxygenates in 5-ml tap water samples. The relative percentage of recoveries of the alkyl ether fuel oxygenates ranged from 97% to 105%. The relative standard deviation ranged from 2% to 6%. Methyl tertiary-butyl ether was detected in samples of tap water taken from geographically diverse regions of the United States. The improved throughput and sensitivity of this method will enable large epidemiologic field studies of the prevalence and magnitude of exposure to alkyl ether fuel oxygenates in the general population.

Introduction

The use of fuel oxygenates was mandated by the Clean Air Act Amendments of 1990. The alkyl ether fuel oxygenates methyl tertiary-butyl ether (MTBE), ethyl tertiary-butyl ether (ETBE), di-isopropyl ether (DIPE), and tertiary-amyl methyl ether (TAME) can all be used to meet the requirement for adding oxygen to gasoline, as required by these regulations. To comply

with this mandate, petroleum production companies initially selected MTBE over the other alkyl ether fuel oxygenates because MTBE was readily available, had a high octane number, and could be easily blended with gasoline. Over a period of 28 years, 1970–1998, chemical manufacturers produced 60 million metric tons of MTBE (1) to meet this need. In 1988, almost 80% of all gasoline contained MTBE (1). The large quantities of MTBE produced in the United States, its widespread use in gasoline, and its solubility in water has resulted in the contamination of both surface and groundwater sources of drinking water (1). MTBE contamination is particularly widespread in the state of California, where it was reported that 40 public drinking water wells, 18 major reservoirs, and approximately 10,000 shallow wells have MTBE contamination in excess of 10 parts per billion (ppb) (3). Surface water clears contamination of MTBE and other alkyl ether fuel oxygenates more quickly through evaporation, mixing, diffusion, and aeration. In contrast, the contamination of ground water by MTBE and other alkyl ether fuel oxygenates is a greater problem because these ethers resist biodegradation and are not retained by the consolidated material comprising various aquifers. The result is that the alkyl ether fuel oxygenates move more rapidly through an aquifer (4) than do other fuel components, and these oxygenates remain at higher levels for longer periods of time than would be the case with surface water contamination. Consequently, a phase-out of alkyl ether fuel oxygenates will not result in an immediate drop in alkyl ether fuel oxygenate levels in ground water. Hence, monitoring for alkyl ether fuel oxygenates, especially MTBE, will need to continue for many years.

Public water supply systems that use ground water as the primary water source supply approximately 91 million people in the United States (5), and the possibility of exposure to MTBE contamination is of public health concern. Additionally, MTBE has very low thresholds for taste and odor, rendering many private and some public wells unusable for drinking. Because of these low thresholds, the Environmental Protection Agency (EPA) has issued a drinking water advisory that recommends MTBE concentrations below 20–40 µg/L to minimize taste and odor prob-

* The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the Centers for Disease Control and Prevention. Although the research described in this article has been supported by the United States Centers for Disease Control and Prevention, no official endorsement should be inferred. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

[†] Author to whom correspondence should be addressed: Frederick L. Cardinali, 4770 Buford Hwy, MS F47, Atlanta, GA 30341; fcardinali@cdc.gov.

lems (6). In 1998–2002 (2), the U.S. Geological Survey completed a survey on the occurrence of MTBE and other fuel oxygenates in untreated ground- and surface-water sources that are available for use by community water systems. This national survey found MTBE contamination in 36 states, primarily in areas with high population density. Contamination by ETBE, DIPE, and TAME was also found, but at much lower concentrations and prevalence than MTBE. The U.S. Geological Survey tested ground water samples from geographically diverse locations in the United States and found detectable DIPE and TAME ($\geq 2 \mu\text{g/L}$) in $< 1\%$ of the approximately 2,300 samples tested. The EPA continues to require that drinking water purification systems monitor for the presence of MTBE, and the agency continues to assess the possible long term health consequences of low-level MTBE exposure through tap water consumption. Currently, five states that account for approximately 45% of MTBE-blended gasoline used in the United States (7) have decided to switch from MTBE to other fuel oxygenates (e.g., ethanol). Despite the phase-out of MTBE, continued exposure as a result of the persistence of this alkyl ether in ground water necessitates analytical methods for measuring MTBE and possible replacement fuel oxygenates.

Our research group has developed a method to assess human exposure to alkyl ether fuel oxygenates by measuring these compounds in whole human blood (8). In order to facilitate studies that compare alkyl ether fuel oxygenate exposure in tap water to the levels found in whole human blood, we needed a high throughput and robust method with good sensitivity. Because our epidemiological studies require hundreds or thousands of samples to be analyzed over a time frame of years, we also wanted to investigate long-term stability of the alkyl ether fuel oxygenate standards and quality control (QC) material.

A search of the literature revealed a number of possible methods for the analysis of fuel oxygenates in water. EPA methods 502 (9), 524 (10), and 551 (11) are used for regulatory purposes for the analysis of volatile compounds in water. However, EPA methods 502 and 524 use the purge-and-trap technique, which requires a larger sample volume than our method. EPA method 551 uses liquid–liquid extraction with MTBE as the recommended primary extraction solvent. However, pentane can be substituted. These three methods have limited sample throughput. EPA method 5021 (12) uses static headspace extraction and has been applied for the analysis of fuel oxygenates in water (13), but also lacks adequate sample throughput. Another approach to the analysis of fuel oxygenates is direct aqueous injection gas chromatography mass spectrometry (DAI-GC-MS) (14). This method has MTBE detection limits of $< 0.2 \mu\text{g/L}$, which is 8 times higher than our method. The run time of 32 min is twice the run time of our method and would also limit the sample throughput needed for our studies. Solid-phase microextraction (SPME) has been used very successfully for the analysis of fuel oxygenates. Cassada et al. (15) manually analyzed all four alkyl fuel oxygenate ethers by using immersion SPME. However, this method was less robust because of the frequent breakage of SPME fibers. Dewsbury et al. (16) developed an automated headspace method for MTBE and TAME, but the method had inadequate throughput (cycle time 55 min) for analysis of large numbers of samples. In response to this recognized

need, we developed a robust, fast, and sensitive method to help assess human exposure to alkyl ether fuel oxygenates.

Experimental

Materials

Methanol, purge and trap (P&T) grade, was purchased from Burdick and Jackson (Muskegon, MI) and used in the preparation of all standards and in rinsing glassware. Luer-Lok, 18-gauge, stainless steel needles were purchased from Becton-Dickinson (Franklin Lakes, NJ). Beveled-top headspace vials (10-mL, serum type) were obtained from Worldwide Glass (Norma, NJ). Thick septa (20-mm, Teflon-faced/silicone) integrated with magnetic cap seals (aluminum, open-center) were purchased from Integrated Liner Technologies (Albany, NY). The vials and septa were treated to remove residual contaminants as per Cardinali et al. (17).

Standards

MTBE, ETBE, DIPE, and TAME were purchased as neat compounds ($> 99\%$, Supelco) and received in flame-sealed ampoules. All compounds were stored at -20°C to minimize degradation. The stable isotope-labeled analog MTBE ($^2\text{H}_{12}$) ($> 99\%$ chemical and isotopic purity, Cambridge Isotope Labs, Andover, MA), ETBE ($^{13}\text{C}_3$), and TAME ($^{13}\text{C}_3$) ($> 99\%$ isotopic purity, ISOTECH, Miamisburg, OH) were purchased as neat compounds in flame-sealed ampoules and stored at -20°C . The chemical purity was 95% and 97% for ETBE ($^{13}\text{C}_3$) and TAME ($^{13}\text{C}_3$), respectively. A stable isotope of DIPE was not available from a commercial source.

Intermediate stock solution concentrations for the standards and labeled analogs were prepared from neat chemicals and diluted with P&T-grade methanol. These stock solutions were aliquoted into glass ampoules, flame-sealed, and stored at -70°C . On the day of use, ampoules of the stock solutions of standards were equilibrated to room temperature. Daily calibration standards were generated by further dilution in helium-sparged–distilled water (18). Solutions of labeled analogs were prepared by further dilution with P&T-grade methanol. Subsequently, 40.0 μL of this final labeled-standard stock solution was added to each blank, standard, unknown, or QC sample being analyzed. Positive displacement pipettors and glass capillary tips were used for all liquid transfers in the microliter range (19).

Water collection vial preparation

The preparation, treatment, and collection procedures used with the Borosilicate glass vials (12-mL, screw cap, Wheaton, Millville, NJ) have been published previously (17).

Water sample collection and storage

The collection procedures for tap water samples have been published previously (17). After collection, the tap water samples were placed in a refrigerator and stored there until shipment to the laboratory.

The amount of air in each water sample was evaluated upon the sample's arrival in the laboratory. A properly collected sample had minimal headspace into which the alkyl ether fuel oxygenates could partition. A previous study by Cardinali et al. (17) showed that air bubbles of up to 2 mL did not lead to significant loss of MTBE ($\leq 5\%$). Because of analyte loss into larger headspace volumes, samples with air bubbles > 2 mL were discarded.

Water sample analysis

The chilled (8–10°C) tap water sample vials were removed from the refrigerator and equilibrated to room temperature before analysis. Immediately after removing the vial cap, we aliquoted the water (5.0 mL) by using a pre-cleaned gas-tight syringe (5-mL, glass, SGE Inc., Austin, TX) and transferred it into a 10-mL beveled SPME headspace vial. Labeled-analog solution (40.0 μ L) was added to the sample, using a positive displacement pipettor (VWR Scientific, Westchester, PA), and the SPME vial immediately was crimp-sealed by use of a thick Teflon-lined septum. The same procedure was applied to blanks, standards, and QC samples. Samples were prepared and analyzed in daily batches of unknowns, 6 calibrators, 2 QC samples, and one blank.

Instrumentation

The high-throughput SPME–GC–MS method was developed on a ThermoFinnigan DSQMS (ThermoFinnigan, Austin, TX) attached to a GC Ultra gas chromatograph equipped with a split/splitless injector, which was operated in the splitless-with-surge mode. The surge pressure was 241 kPa for a duration of 2 min. A 0.75-mm i.d. SPME injection port liner was used. A cryo-trap (model 961, Scientific Instrument Services, Ringoes, NJ) attached to the bottom of the injector port was used to cryofocus the volatile compounds at the head of the GC column. With liquid nitrogen as the coolant, the cryo-trap was maintained at -60°C for the first 1 min of analysis. Then the trap was heated ballistically to 200°C to begin chromatographic separation on a VRX capillary column (30-m \times 0.25-mm i.d. \times 1.4- μ m film, Restek, Bellefonte, PA). The GC oven was equipped with a liquid nitrogen coolant valve to enable a subambient initial oven temperature (0°C). A constant flow of 1.0 mL/min was maintained by use of helium (Research grade, 99.9999%, Airgas South, Atlanta, GA) as the carrier gas. The GC was held at an initial temperature of 0°C , followed by a linear thermal gradient of $30^\circ\text{C}/\text{min}$ to 100°C , then $50^\circ\text{C}/\text{min}$ to 200°C and held for 2 min. Automated headspace sampling was done by using a CombiPAL autosampler (CTC Analytics AG, Zwingen, Switzerland) equipped with a 75- μ m Carboxen–polydimethylsiloxane (PDMS) SPME fiber assembly (Supelco, Bellefonte, PA). Before each sample set was analyzed, the Carboxen–PDMS fiber was preconditioned as per Cardinali et al (17). After preparation, samples were queued in a Peltier cooled rack ($15 \pm 1^\circ\text{C}$) before analysis. We began sample analysis by moving the active sample to a heated agitator station (50°C). Following pre-incubation (10 s), the SPME fiber was inserted into the vial headspace and the sample was extracted for 5 min at 500 rpm. The extraction time of 5 min was adequate for good signal-to-noise ratio; it avoided the excessive water vapor suppression of MTBE (17). The labeled internal standards added

to the samples compensate for the non-equilibrium extraction time used in our method. The fiber was promptly desorbed by insertion into the hot GC inlet (220°C). The SPME fiber remained in the GC inlet for the remainder of the GC analysis run to ensure complete analyte desorption and to minimize contamination from laboratory air.

The mass spectrometer was equipped with an electron-impact source and operated in the selected ion monitoring (SIM) mode (Table I). As each analyte eluted from the GC column, the mass spectrometer measured three ions: one each for quantitation, confirmation, and the stable isotope-labeled internal standard. Quantitation ions were selected as the most abundant ion in the mass spectrum that did not compromise the specificity of the analysis. We determined the retention time for each compound by analyzing known standards in full-scan mode and adjusting the SIM windows accordingly. Cycle time per sample was 15 min.

Quantitation

Xcalibur Quan software (ThermoFinnigan) was used for peak integration, calibration, and quantitation. Peak integrations were performed with the interactive chemical information system (ICIS) integrator software and confirmed by visual inspection. Relative response factors were calculated on the basis of relative peak areas of the analyte-quantification ion and the labeled-analog ion. The data from the set of six calibrators analyzed with each set of samples were processed by using $1/x$ weighing and linear calibration to generate the calibration curve for that day. These calibration curves were linear ($r^2 \geq 0.99$), spanning three orders of magnitude as shown in Table II. Calibration curves were adjusted for ion cross-contamination between native analyte and isotopic analog according to Colby and McCaman (20). The limit of detection (LOD) was calculated as 3 times the standard deviation at zero concentration ($3S_0$) (21). If $3S_0$ was less than the lowest standard, then the lowest standard served as the lowest reported value. The lowest reported value for each of the four alkyl ether fuel oxygenates varied from 0.025 $\mu\text{g}/\text{L}$ to 0.026 $\mu\text{g}/\text{L}$ as shown in Table II.

Quality assurance

Data were subjected to rigorous quality assurance (QA) procedures by use of a custom laboratory information management system constructed in Microsoft Access. Before analysis of samples, the mass spectrometer was tuned against perfluorotri-*N*-butylamine (PFTBA) calibration gas, using the autotune function to ensure proper mass calibration. Contamination was evaluated both qualitatively and quantitatively. Laboratory air was extracted by using SPME for 5 min, then desorbed into the GC–MS as described above. The resulting chromatograms were qualitatively reviewed for the presence of gross contamination of MTBE, DIPE, ETBE, and TAME. The analysis of a water sample free of alkyl ether fuel oxygenates was used to quantify any trace contamination of the analytes. Following sample analysis and the visual inspection of every integrated peak, additional QA parameters were evaluated. Adequate labeled analog response was evaluated on the basis of absolute peak area signal as well as signal-to-noise ratio. We further evaluated the identity of the analyte ion by comparing the confirmation ion/quantification ion ratio in unknown samples with that for reference standards.

Table I. Mass Spectrometry Parameters for the Analysis of Alkyl Ether Fuel Oxygenates in Household Tap Water

Compound (label configuration)	Labeled standard mass (m/z)	Analyte mass (m/z)	Confirmation mass (m/z)	Dwell time per mass (msec)	Retention times (min)
Methyl tertiary-butyl ether ($^2\text{H}_{12}$)	82			50	3.02
Methyl tertiary-butyl ether		73	74	50	3.08
Di-isopropyl ether ($^{13}\text{C}_3$)	89	59	87	50	3.36
Ethyl tertiary-butyl ether ($^{13}\text{C}_3$)	89	59	57	50	3.52
Tertiary-amyl methyl ether ($^{13}\text{C}_3$)	75	73	87	50	3.96

Each batch of data also was judged against blind QC samples.

QC samples

Two QC samples were processed and analyzed with each batch of samples. We prepared these aqueous samples from concentrated standards made with P&T-grade methanol. The low QC concentrations were: MTBE, 3.19 $\mu\text{g/L}$; DIPE, 3.12 $\mu\text{g/L}$; ETBE, 3.27 $\mu\text{g/L}$; and TAME, 3.11 $\mu\text{g/L}$. The high QC concentrations were: MTBE, 31.92 $\mu\text{g/L}$; DIPE, 31.28 $\mu\text{g/L}$; ETBE, 32.71 $\mu\text{g/L}$ and TAME, 31.13 $\mu\text{g/L}$. The low and high QCs had been prepared previously by weighing neat material into volumetric flasks containing P&T-grade methanol and storing them at -70°C as aliquots in flame-sealed glass ampoules. On the day of use, we further diluted these stock solutions in helium-sparged, distilled water, and the resulting material was sampled as though it were an unknown. Two QC pools were prepared (high and low levels) and characterized by 15 separate determinations. Blind QC samples were evaluated by an independent QC officer according to Westgard QC rules (22). If a QC sample exceeded QC limits for an analyte, then all results for that analyte on that day were rejected.

Contamination control and blank analysis

Of the four alkyl ether fuel oxygenates, MTBE can be the most ubiquitous in a typical laboratory, depending on the nature of the work being carried out. Therefore, rigorous techniques are required to minimize laboratory air contamination of the MTBE samples. Potential sources of contamination include common household cleaning products, laboratory solvent usage, and oxygenated fuel usage. MTBE from these sources and others can spread through laboratory air to contaminate the samples during preparation or the SPME fiber during analysis. Contamination was minimized by removing possible external sources of alkyl ether fuel oxygenates from the laboratories where samples were prepared and analyzed. MTBE contamination of water samples can also occur if the water samples come in contact with items made of polypropylene (e.g., pipette tips or containers) (17). To prevent contamination from polypropylene, only borosilicate glass containers and pipette tips were used. Another source of possible MTBE contamination is the septa used to seal the SPME vials (23); the curing agent used to make some brands of septa generates MTBE as a by-product. Therefore, we prescreened all septa to avoid this problem.

A blank water sample was used to test for contamination. Blank water was prepared by helium sparging, distillation, and storage in 125-mL

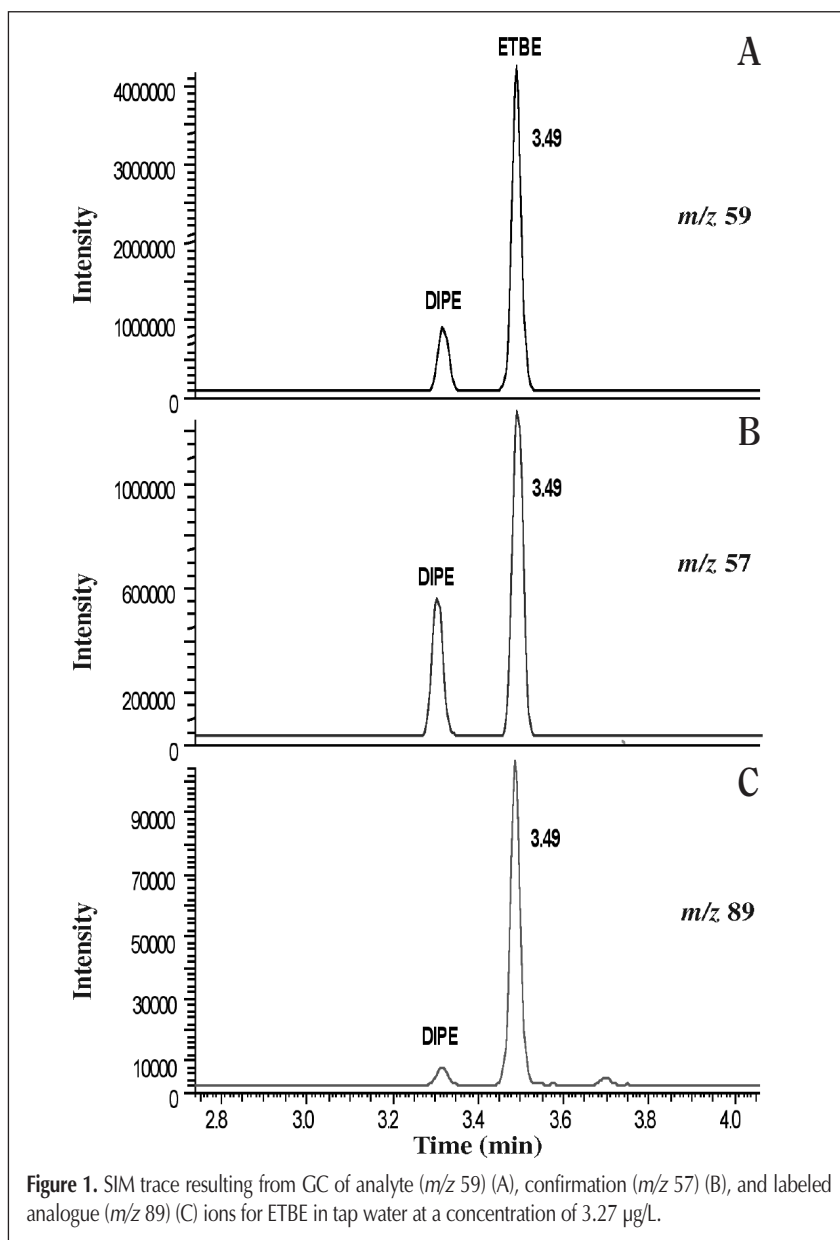


Figure 1. SIM trace resulting from GC of analyte (m/z 59) (A), confirmation (m/z 57) (B), and labeled analogue (m/z 89) (C) ions for ETBE in tap water at a concentration of 3.27 $\mu\text{g/L}$.

brown glass bottles sealed with a Teflon-lined screw cap. On the day of use, a 5 mL aliquot of blank water was removed, spiked with labeled analog, and analyzed with each batch of unknowns. If the blank contained analyte levels of at least half of the LOD, then the analytical run was flagged as contaminated. Additionally, an SPME fiber sampling of laboratory air was analyzed to assess airborne contaminants qualitatively.

Results and Discussion

Method Validity

Figure 1 shows GC traces of ETBE resulting from the analysis of a tap-water sample fortified with MTBE, DIPE, ETBE, and TAME. The quantification (m/z 59), confirmation (m/z 57), and labeled analog (m/z 89) ions of ETBE are well resolved from DIPE and potential interfering compounds. Because this analysis relies on a relatively short GC analysis run time and the elution of all four analytes within a 1-min window, the possibility of unknown co-eluting peaks had to be considered. Therefore, appropriate selection of the quantification, confirmation, and labeled analog ions was crucial. For example, the initial selection of m/z 87 as the quantification ion for ETBE produced erratic results. The problem was traced to chloroform, which co-elutes with ETBE. Chloroform forms in part-per-billion concentrations during water chlorination and fragments to produce an m/z 87

ion that can overwhelm the m/z 87 signal from part-per-trillion levels of ETBE. Substituting m/z 59 for the quantification ion and m/z 57 as the confirmation ion resolved this problem. We also analyzed a standard containing bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform, disinfection byproducts that are often found in chlorinated water. We used the same alkyl ether fuel oxygenates GC method. BDCM, DBCM, and bromoform all eluted after TAME and did not interfere. This excellent selectivity was also achieved for the other three fuel oxygenates; it resulted from the combination of a selective detector, chromatographic resolution, and a relatively simple matrix.

In order to prevent the on-going formation of trihalo-methanes after water samples are collected for analysis, buffer-quench solution is added to the sample-collection vials (17). The use of buffer-quench solution to preserve water samples for the analysis of alkyl ether fuel oxygenates would not seem necessary because free chlorine does not attack these compounds. However, Diaz et al. reported (24) hydrolysis of alkyl ether fuel oxygenates under acidic conditions. Because the buffer-quench solution maintains the water samples at approximately pH 6.5, hydrolysis of the alkyl ether fuel oxygenates does not occur and sample integrity is maintained. In fact, we previously reported that MTBE in buffered tap water samples is stable for more than a year (17).

We evaluated the suitability of the method for detecting alkyl ether fuel oxygenates in 16 tap water samples collected from 16 geographically diverse regions around the United States. MTBE was detected in these samples ranging from 0.09–0.25 $\mu\text{g/L}$. However, DIPE, ETBE, and TAME were not detected. These results are consistent with water data collected by the United States Geological Survey as part of the National Water-Quality Assessment (NAWQA) program. In this study of 2,300 US ground water samples, DIPE and TAME were detected in only 0.3% of samples and ETBE was not detected. The USGS NAWQA study used a method with an LOD of 0.2 $\mu\text{g/L}$ (2), 8-fold higher than the LOD of the method we present here. Our method is also more sensitive than EPA method 524.2 (LOD = 1.2 $\mu\text{g/L}$) (25) and certainly adequate for measuring fuel oxygenate contamination above the minimal odor and taste thresholds for these compounds (10 $\mu\text{g/L}$). The method is also adequately sensitive to detect alkyl ethyl fuel oxygenates above the EPA's minimal drinking water advisory level of 20 $\mu\text{g/L}$ (26). Thus, the LODs for the four fuel oxygenates listed in Table II are adequate to identify levels of public health concern.

Assay precision was evaluated by analyzing QC samples of known composition (Table III). The relative standard deviation (RSD) ranged from 3%–6% across the characterized levels of QC samples. Over a 15-day period, the RSD of the slope of the daily calibration curves ranged from 4.3% to 9.9%, depending on the analyte. As a measure of the accuracy of this method, we calculated the theoretical concentrations of the low and high QC samples based on the original weights, then compared these values to the

Table II. LODs, Lowest Reportable Values, and Calibration Ranges

Analyte	LOD (3S ₀) ($\mu\text{g/L}$)	Lowest reportable value ($\mu\text{g/L}$)	Calibration range ($\mu\text{g/L}$)
MTBE	0.011	0.025	0.025–31.9
DIPE	0.007	0.025	0.025–32.1
ETBE	0.011	0.026	0.026–32.70
TAME	0.015	0.025	0.025–31.1

Table III. Assay Precision and Accuracy Based on Replicate Analysis ($n = 15$) of QC* Pools

Analyte	QC pool	Analyte level ($\mu\text{g/L}$)	Calculated analyte level ($\mu\text{g/L}$)	RSD [†]	Accuracy [‡]	Inter-Day RSD	Intra-Day RSD
MTBE	High	31.92	33.66	6.2%	105%	6.6%	2.4%
	Low	3.19	3.09	4.3%	97%	4.5%	1.9%
DIPE	High	31.28	32.48	6.2%	104%	4.9%	6.2%
	Low	3.12	3.19	4.7%	102%	4.6%	3.0%
ETBE	High	32.71	32.84	3.1%	100%	3.2%	1.4%
	Low	3.27	3.44	2.4%	105%	1.8%	2.6%
TAME	High	31.13	31.59	4.2%	102%	3.9%	2.9%
	Low	3.11	3.26	2.8%	105%	2.2%	3.0%

* Quality Control.

[†] Relative Standard Deviation.

[‡] Relative recovery of calculated theoretical concentration, based on dilution of neat standard materials. Labeled internal standards compensate for the limited capacity of the SPME fiber.

mean QC concentrations determined by this method (Table III). Relative percent recoveries ranged from 97% to 105%, demonstrating the ability of this method to generate valid data for alkyl fuel ether oxygenates in water.

To further validate this method, household tap-water samples were spiked with known amounts of the four alkyl ether fuel oxygenates and analyzed in triplicate on six different days. These tap water samples had an average residual free chlorine level of 0.8 ppm and a pH of 6 before buffer-quench solution was added. Table IV shows the results from these experiments. Recoveries varied from 87%–106%, with MTBE showing the lowest relative recovery in this experiment (87%). This result may be due to the use of a deuterated labeled internal standard for MTBE instead of the ^{13}C -labeled standard that was used for the other analytes. With deuterium labeling, the internal standard elutes before the native MTBE and may not always correct for differential ion suppression. This may be the cause of the negative percent differences between the expected and calculated standard values in tap water samples compared to standards analyzed in helium-sparged/distilled water.

Long term stability of calibration standards

Because exposure studies can extend for years, it is critical that the calibration standards, QC material, and labeled internal standards be stable for extended periods of time. To verify the stability of our standards over time, we analyzed solutions of alkyl ether fuel oxygenates that had been stored at -70°C for 6.5 years. These four different solutions had been flame-sealed in 1-mL borosilicate glass ampoules that contained MTBE, ETBE, DIPE, and TAME at concentrations ranging from 0.1 $\mu\text{g/L}$ to 5 $\mu\text{g/L}$. The calibrators were analyzed in triplicate on two different days. The average percent differences between the theoretical values for the four calibrators and the calculated values were -7% , 5% , -12% , and 5% for MTBE, ETBE, DIPE and TAME, respectively. These results showed that the alkyl ether fuel oxygenates are stable when stored frozen for over 6 years. The ability to analyze samples, calibration standards, QC material, and labeled internal standards over extended periods of time will improve long-term exposure studies.

Because our method uses a simple water matrix and measures only volatile compounds, interferences should be minimal. However, other volatile components in high enough concentra-

tions could cause ion suppression of the fuel oxygenates, resulting in false negatives, retention time shifts, or other detrimental effects on the analysis of these compounds. With the wide variation in environmental conditions under which surface or ground water can exist, quantitative validity of the method will need to be reassessed for new water sources.

Our method improves on existing alkyl ether fuel oxygenate methods by improving throughput and reducing sample handling, while maintaining sensitivity. This method will enable large epidemiologic field studies of the prevalence and magnitude of exposure to alkyl ether fuel oxygenates in the general population.

References

1. J.M. Carter, S.J. Grady, G.C. Delzer, B. Koch and J.S. Zogorski. Occurrence of MTBE and other gasoline oxygenates in CWS source waters. *AWWA* **98(4)**: 91–104 (2006)
2. M.J. Moran, J.S. Zogorski, and P.J. Squillace. Occurrence and implications of methyl tert-butyl ether and gasoline hydrocarbons in ground water and source water in the United States in drinking water in 12 Northeast and Mid-Atlantic States, 1993-2002: U.S. Geological Water-Resources Investigations Report 03-4200, 26 p (2004).
3. A.F. Diaz and D.L. Drogos. "Stability of Methyl tert-Butyl Ether, tert-Amyl Methyl Ether, and Ethyl tert-Butyl Ether in Acidic Media". In *Oxygenates in Gasoline: Environmental Aspects*, ACS Symposium Series 799. A.F. Diaz and D.L. Drogos, Ed. American Chemical Society, Washington, D.C., 2002, p. 140.
4. R.A. Freeze and J.A. Cherry. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1979.
5. J.H. Farrelly. Status of source water protection. *Ground Water Monitoring and Remediation* **22(3)**: 50–51 (2002).
6. U.S. Environmental Protection Agency. Drinking water advisory consumer acceptability advice and health effects analysis on methyl tertiary-butyl ether, EPA-822-F-97-009. U.S. EPA, Office of Water, Washington, D.C. (1997).
7. Energy Information Administration, DOE. Status and impact of state MTBE ban. 2003.
8. L. Silva, C.R. Wilburn, M.A. Bonin, M.M. Smith, K.A. Reese, D.L. Ashley and B.C. Blount. Quantification of fuel oxygenate ethers in human blood using solid-phase microextraction coupled with gas chromatography-high resolution mass spectrometry. *J. Anal. Toxicol.* **32**: 147–154 (2008).
9. United States Environmental Protection Agency. EPA Method 502.2, Rev. 2.1 (1995).
10. United States Environmental Protection Agency. EPA Method 524.2, Rev. 2.1 (1995).
11. United States Environmental Protection Agency. EPA Method 551.1, Rev. 1.0 (1995).
12. United States Environmental Protection Agency. EPA Method 5021 (1996).
13. Z. Lin, J.T. Wilson and D.D. Fine. Avoiding hydrolysis of fuel ether oxygenates during static headspace analysis. *Environ. Sci. Technol.* **37**: 4994–5000 (2003).
14. L. Zwank, T.C. Schmidt, S.B. Haderlein, and M. Berg. Simultaneous determination of fuel oxygenates and BTEX using direct aqueous injection gas chromatography mass spectrometry (DAI-GC/MS). *Environ. Sci. Technol.* **36**: 2054–2059 (2002).
15. D.A. Cassada, Y. Zhang, D.D. Snow, and R.F. Spalding. Trace analysis of ethanol, MTBE and related oxygenate compounds in water using solid-phase microextraction and gas chromatography/mass spectrometry. *Anal. Chem.* **72(19)**: 4654–4658 (2000).

Table IV. Assay Precision and Accuracy Based on Replicate Analysis of Spiked Household Tap Water Samples ($n = 18$)

Analyte	Analyte level ($\mu\text{g/L}$)	RSD*	Accuracy (%)†
Methyl tertiary-butyl ether	0.319	6.4%	87%
Di-isopropyl ether	0.312	6.9%	100%
Ethyl tertiary-butyl ether	0.327	4.1%	106%
Tertiary-amyl methyl ether	0.311	2.8%	102%

* Relative Standard Deviation

† Relative recovery of calculated theoretical concentration based on dilution of neat standard materials in household tap water. Labeled internal standards compensate for the limited capacity of the SPME fiber.

16. P. Dewsbury, S.F. Thornton, and D.N. Lerner. Improved analysis of MTBE, TAME and TBA in petroleum fuel-contaminated groundwater by SPME using deuterated internal standards with GC-MS. *Environ. Sci. Technol.* **37**: 1393-97 (2003).
17. F.L. Cardinali, D.L. Ashley, J.C. Morrow, D.M. Moll, and B.C. Blount. Measurement of trihalomethanes and methyl tertiary-butyl ether in tap water using solid-phase microextraction GC-MS. *J. Chromatogr. Sci.* **42**: 200-206 (2004).
18. F.L. Cardinali, J.M. McCraw, D.L. Ashley and M.A. Bonin. Production of blank water for the analysis of volatile organic compounds in human blood at the low parts-per-trillion level. *J. Chromatogr. Sci.* **32**: 41-44 (1994).
19. D. L. Ashley, M. A. Bonin, F. L. Cardinali, J. M. McCraw, J. L. Holler, L. L. Needham, and D. G. Patterson Jr. Determining volatile organic compounds in human blood from a large sample population by using purge and trap gas chromatography/mass spectrometry. *Anal. Chem.* **64**: 1021-29 (1992).
20. B.N. Colby and M.W. McCaman. A comparison of calculation procedures for isotope dilution determinations using gas chromatography mass spectrometry. *Biomed. Mass Spectrom.* **6**: 225-30 (1979).
21. J.K. Taylor. *Quality Assurance of Chemical Measurements*. Lewis Publishers, Chelsea, MI, 1987, pp 79-82.
22. J.O. Westgard, P.L. Barry, M. R. Hunt, and T. Groth. A multi-rule Shewhart chart for quality control in clinical chemistry. *Clin. Chem.* **27(3)**: 493-501 (1981).
23. D.M. Chambers, D.O. McElprang, J.P. Mauldin, T.M. Hughes, and B.C. Blount. Identification and elimination of polysiloxane curing agent interference encountered in the quantification of low-picogram per milliliter methyl tert-butyl ether in blood by solid-phase microextraction headspace analysis. *Anal. Chem.* **77**: 2912-2919 (2005).
24. A.F. Diaz and D.L. Drogos. Stability of methyl tert-butyl ether, tert-amyl methyl ether, and ethyl tert-butyl ether in acidic media. In *Oxygenates in Gasoline: Environmental Aspects*, ACS Symposium Series 799. A.F. Diaz and D.L. Drogos, Ed. American Chemical Society, Washington, D.C., 2002, pp. 138-145.
25. U. S. Environmental Protection Agency. EPA Method 524.2, Rev. 4.2 (1995).
26. U.S. Environmental Protection Agency. Regulatory Determinations Support Document for Selected Contaminants from the Second Water Contaminant Candidate List (CCL 2), EPA-Report 815-D-06-007. U.S. EPA, Office of Ground Water and Drinking Water, Washington, D.C. (2006).

Manuscript received December 10, 2007;
revision received January 17, 2008.