Comparison of Helium-Alternative Carrier Gases for Gas Chromatography/Mass Spectrometry of Standard Test Methods for Indoor Air Quality Guidelines in Japan

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Helium is the most frequently used carrier gas for GC/MS, which is the official standardized test method in Japan to assess chemical substances in indoor air. However, recent global challenges in the supply chain for helium have led to a need to validate GC/MS using alternative carrier gases. In this study, we examined the applicability of hydrogen and nitrogen as helium-alternative carrier gases in the standardized GC/MS analytical test method for volatile organic compounds (VOC) and phthalate esters in indoor air. Comparison of the signal-to-noise ratios of standard solutions showed that detection sensitivities of hydrogen and nitrogen analysis were enough for the standard test method, although these gases, especially nitrogen, were less sensitive than helium. Measurements using these alternative carrier gases showed good linearity and could quantify around 1/100th of Japanese guideline values for indoor air concentrations. Therefore, hydrogen and nitrogen gases can be applied to the standard GC/MS analysis test method for VOC and phthalate esters in indoor air as alternative carrier gases to helium.

Key words indoor air, helium, alternative carrier gas, volatile organic compounds, phthalate esters

INTRODUCTION

Chemical substances in indoor air are widely analyzed by GC/MS, and helium is the carrier gas most frequently used. Although helium is easy to handle and has a high analytical performance because it is inert and non-flammable, Japan imports its entire supply of helium, and this is becoming difficult due to recent global supply chain issues.1–4) Hydrogen and nitrogen are helium-alternative carrier gases that are attracting attention because of their stable supply in contrast to noble gases such as helium. Studies on GC/MS analysis with hydrogen and nitrogen have been reported,5–8) and many instrument companies have developed GC/MS analytical equipment that can use both as carrier gases in recent years. Thus, GC/MS analyses with hydrogen and nitrogen are becoming possible with a degree of safety and high performance.

Previously, we developed a standardized test method of GC/MS for chemical substances in indoor air and promoted national and international standardization of the test method. Additionally, the Committee on Sick House Syndrome: Indoor Air Pollution (CIAP) has set and revised the guideline values for indoor air concentration in Japan to prevent health deterioration caused by indoor air pollution.9) However, the current standardized method to assess chemicals in indoor air has specified the carrier gas as helium, which has an unstable supply. Therefore, validation of GC/MS with carrier gases that can be supplied stably has become urgently required in the face of restrictions on the use of helium.

In this study, we examined the applicability of hydrogen and nitrogen as helium-alternative carrier gases for GC/MS for chemicals in indoor air, including volatile organic compounds (VOC) such as toluene and semi-volatile organic compounds (SVOC) such as phthalate esters.

MATERIALS AND METHODS

Chemicals Standard solutions were purchased from Tokyo Chemical Industry Co. (Tokyo, Japan), Fujifilm Wako Pure Chemicals Co. (Osaka, Japan), and Kanto Chemical Co. (Tokyo, Japan). Toluene-d₈ (Fujifilm Wako Pure Chemicals Co., Osaka, Japan) for VOC and di-n-butyl phthalate-d₄ (DnBP-d₄), di-2-ethylhexyl phthalate-d₁₂ (DEHP-d₁₂) for SVOC were used as internal standard substances. Methanol (MeOH), testing after 5,000-fold concentrated for pesticide residue and poly chlorinated biphenyl analysis, was purchased from Fujifilm Wako Pure Chemicals Co. (Osaka, Japan) and Kanto Chemical Co. (Tokyo, Japan).

Instruments GC/MS analysis was performed using the Agilent 5977B GC/MSD series with the PAL3 RSI Autosampler system (Agilent Technologies, Inc., CA, USA). The NM Plus 160 Hydrogen Generator (Airtech Co., Kanagawa, Japan) was used to supply hydrogen as the carrier gas.

Analytical Methods The analytical conditions of GC were determined in accordance with the “Manual for Measuring Indoor Air Chemical Substances” set by CIAP,10) and were modified for each alternative carrier gas with reference to EZGC Method Translator and Flow Calculator (Restek Corporation, PA, USA).
The targeted chemicals were toluene, xylene, styrene, ethylbenzene, 1,4-dichlorobenzene, tetradecane as VOC and di-n-butyl phthalate (DnBP), and di-2-ethylhexyl phthalate (DEHP) for SVOC (Fig. 1). These target and qualifier ions are shown in Table 1. These chemicals were measured using Selected Ion Monitoring (SIM) modes and were quantified based on internal standard methods using toluene-\textsubscript{d8} for VOC and DnBP-\textsubscript{d4} and DEHP-\textsubscript{d4} for phthalate esters. The concentration range of the calibration curve was 0.5–100 ng. m\textsuperscript{-2}. The limits of detection (LOD) and those of quantification (LOQ) were calculated as 3-fold, 10-fold the standard deviation of five analyses of the lowest concentration samples (0.1 ng), respectively, and were further divided by the expected sampling volume according to the standard test method specified by the CIAP, MHLW.\textsuperscript{10} The details of the measurement conditions are shown in Table 2.

**Table 1. Target and Qualifier Ions**

| Chemicals     | Target Ion | Qualifier Ion |
|---------------|------------|---------------|
| Toluene       | 91         | 65, 92        |
| Xylene        | 91         | 105, 106      |
| Styrene       | 104        | 78, 103       |
| Ethylbenzene  | 91         | 51, 106       |
| 1,4-Dichlorobenzene | 146    | 111, 148     |
| Tetradecane   | 57         | 43, 71        |
| Toluene-\textsubscript{d8} | 98       | 70, 100       |
| DnBP          | 149        | 223           |
| DEHP          | 149        | 167           |
| DnBP-\textsubscript{d4} | 153    | 227           |
| DEHP-\textsubscript{d4} | 153    | 171           |

**Table 2. Measurement Conditions**

(A) VOC

| Carrier gases | He | H\textsubscript{2} | N\textsubscript{2} |
|---------------|----|-----------------|------------------|
| **Sampling conditions** | | | |
| Expected air volume | 144 L (0.1 L/min, 24 h) | | |
| Expected extraction volume | 1 mL | | |
| **Analytical conditions** | | | |
| Column | Rtx\textsuperscript{5}-1 (0.32 mm i.d. × 60 m, 1 μm) | Rtx\textsuperscript{5}-1MS (0.25 mm i.d. × 60 m, 1 μm) | |
| Time | 45 min | 52.5 min | 105 min |
| Gradient mode | 40°C→(5°C/min)→250°C | 40°C→(4°C/min)→250°C | 40°C→(2°C/min)→250°C |
| Inlet temperature | 280°C | | |
| Source temperature | 230°C | | |
| Quad temperature | 150°C | | |
| Linear velocity (cm/sec) | 36.5 | 36.5 | 18.9 |
| Flow (mL/min) | 2 | 0.92 | 0.5 |
| Inlet pressure (kPa) | 12.3 | 5.4 | 6 |
| Split ratio | 20:1 | | 10:1 |
| Acquision type | SIM/Scan | | |
| Range (m/z) | 35–450 | | |
| Injection volume | 1.0 μL | | |

(B) Phthalate esters

| Carrier gases | He | H\textsubscript{2} | N\textsubscript{2} |
|---------------|----|-----------------|------------------|
| **Sampling conditions** | | | |
| Expected air volume | 4,320 L (3 L/min, 24 h) | | |
| Expected extraction volume | 5 mL | | |
| **Analytical conditions** | | | |
| Column | DB-1 (0.25 mm i.d. × 15 m, 0.10 μm) | DB-1MS (0.18 mm i.d. × 20 m, 0.18 μm) | |
| Time | 30 min | 18 min | 35 min |
| Gradient mode | 80°C (2 min)→(8°C/min)→210°C (5 min) | 80°C (1 min)→(26°C/min)→210°C (3 min)→(40°C/min)→250°C (8 min) | 80°C (2 min)→(13°C/min)→210°C (5 min)→(20°C/min)→250°C (16 min) |
| Inlet temperature | 250°C | | |
| Source temperature | 230°C | | |
| Quad temperature | 150°C | | |
| Linear velocity (cm/sec) | 67.6 | 57.8 | 28.5 |
| Flow (mL/min) | 1.67 | 0.74 | 0.36 |
| Inlet pressure (kPa) | 50 | | |
| Split ratio | Splitless | | |
| Acquision type | SIM/Scan | | |
| Range (m/z) | 35–450 | | |
| Injection volume | 1.0 μL | | |
RESULTS AND DISCUSSION

The SIM chromatograms of the standard solutions for the targeted chemicals showed that the peaks had good separation for qualitative and quantitative analysis for all tested carrier gases (Fig. 2). The signal-to-noise (S/N) ratios of the measurements with 100 ng of the targeted chemicals are shown in Table 3. The S/N ratio was the highest for helium, followed by hydrogen, which was 55%–93% lower than that of helium, and nitrogen, which was 93%–98% lower than that of helium. The reason for the extremely low sensitivity of nitrogen is suspected to be the lower vacuum pressure.

The coefficients of determination ($R^2$) of the calibration curves are shown in Table 4. Most of the chemicals showed good linearities, even the least sensitive nitrogen carrier gas with an $R^2$ of 0.9917–0.9998 in the concentration range of 0.1–100 μg/mL for VOC and 0.1–5 μg/mL for phthalate esters. However, as the $R^2$ of tetradeacne was below 0.99, the concentration range was changed to 0.1–20 μg/mL to give an $R^2$ of 0.9948.

A comparison of the LOD, LOQ, and guideline values for indoor air concentrations is shown in Table 5. The LOQ of all chemicals was less than 1/100th of guideline values, except for xylene with helium carrier gas and for toluene, xylene, and tetradeacne with nitrogen. However, the LOQ of xylene with helium was 2.40 μg/m$^3$, and that of toluene, xylene, and tetradeacne with nitrogen were 3.40 μg/m$^3$, 7.20 μg/m$^3$, and 5.90 μg/m$^3$, respectively, revealing that these LOQs were close to 1/100th of the guideline values. Therefore, measurements using any of these carrier gases can quantify around 1/100th of the guideline values for the indoor air concentrations of all tested chemicals.

Herein, we found that the analysis results using hydrogen as a carrier gas were comparable to those of helium, suggesting that hydrogen is a promising alternative to helium in the standard GC/MS test method for chemicals in indoor air. Meanwhile, nitrogen was clearly less sensitive than helium, and it might be difficult to conduct non-targeted analyses at the current level of an analytical equipment. However, target...
Table 3. S/N Ratios of the Targeted Chemicals

| Chemicals          | S/N ratio* |
|--------------------|------------|
|                    | He         | H₂         | N₂     |
| Toluene            | 20,544     | 1,392      | 1,416  |
| Ethylbenzene       | 32,635     | 2,660      | 1,714  |
| m,p-Xylene         | 37,030     | 2,850      | 1,472  |
| o-Xylene           | 29,770     | 2,465      | 1,447  |
| Styrene            | 31,055     | 5,384      | 1,115  |
| 1,4-Dichlorobenzene| 68,362     | 6,289      | 1,287  |
| Tetradecane        | 29,086     | 11,650     | 520    |
| DnBP*              | 48,249     | 9,500      | 1,087  |
| DEHP*              | 12,193     | 5,429      | 589    |

*100 µg/mL, 1 µL inj.

Table 5. Comparison of LOD, LOQ, and the Guideline Values for Indoor Air Concentration

| Chemicals | LOD (µg/m³) | LOQ (µg/m³) | Guideline values (µg/m³) |
|-----------|-------------|-------------|--------------------------|
|           | He          | H₂          | N₂          | He          | H₂          | N₂          | |
| Toluene*  | 0.064       | 0.034       | 1.02        | 0.21        | 0.11        | 3.40        | 260         |
| Ethylbenzene* | 0.20       | 0.15        | 0.70        | 0.65        | 0.49        | 2.30        | 3,800       |
| Xylene*   | 0.72        | 0.27        | 2.17        | 2.40        | 0.90        | 7.20        | 200         |
| Styrene*  | 0.53        | 0.14        | 0.37        | 1.80        | 0.47        | 1.20        | 220         |
| 1,4-Dichlorobenzene* | 0.70     | 0.17        | 0.46        | 2.30        | 0.56        | 1.50        | 240         |
| Tetradecane* | 0.29       | 0.20        | 1.80        | 0.96        | 0.66        | 5.90        | 330         |
| DnBP§     | 0.0014      | 0.012       | 0.018       | 0.0047      | 0.039       | 0.059       | 17          |
| DEHP§     | 0.0024      | 0.0030      | 0.018       | 0.0080      | 0.010       | 0.059       | 100         |

*0.1 ng injection at five times repeatedly
* Divided by 144 L specified collection volume for VOC in indoor air
§ Divided by 4,320 L specified collection volume for phthalate esters in indoor air

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