Applications of Hadamard Transform-Gas Chromatography/ Mass Spectrometry (HT-GC/MS) to the Detection of Pesticides in Rice

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1. Introduction

The levels of pesticide residues in rice and the standard operating procedures (SOP) for these are often stipulated in many countries (Pareja *et al*., 2011a; Pareja *et al*., 2011b). The conventional analysis of pesticide residues is a labor intensive procedure, since it is necessary to cover a wide range of different chemicals, using a single procedure. These traditional labor intensive extraction methods, such as liquid-liquid extraction, solid-phase extraction and accelerated solvent extraction are still used, whereas the use of the Quick Easy Cheap Effective Rugged and Safe (QuEChERS) pesticide multiresidue method is economic and fast (Pareja *et al*., 2011b; Mastovska *et al*., 2010; García-Reyes *et al*., 2009). It has been validated for the extraction of 80 pesticides belonging to various chemical classes from various types of representative commodities with low lipid contents. However, supercritical fluid extraction (SFE) is also a popular method for pesticide extraction from foods (Kim *et al*., 1998; Izquierdo *et al*., 1996; Anastassiades and Schwack, 1998; Eller and Lehotay, 1997; Lehotay, 1997; Bernal *et al*., 2008; France *et al*., 1991; Goli *et al*., 1997). The advantages of SFE are well-known by now, including savings in labor, operational costs, laboratory space, waste minimization and increased selectivity versus traditional methods (Wang and Chang, 1998; Giddings *et al*., 1968; Hawthorne, 1990). When using SFE, in many cases the extracts should be further examined by GC/MS (gas chromatography/mass spectrometry) or HPLC/MS (high-performance liquid chromatography/mass spectrometry) to achieve the necessary selectivity and sensitivity for the different classes of compounds under detection (Hansen *et al*., 1995; Blanch *et al*., 1995; Jacques *et al*., 2007; Seger *et al*., 2004; Stolker *et al*., 2003). In this work, we developed a novel method by combining an on-line sample SFE collection system and the Hadamard transform GC/MS (HT-GC/MS) method for the extraction/detection of pesticide in rice (Fan *et al*., 2010; Johansen *et al*., 1994; Fuoco *et al*., 1997; Aguilera *et al*., 2005; Gmuer *et al*., 1987). The methodology of HT-GC/MS and the design of an on-line SFE sample collection system are demonstrated. Details of the experimental conditions for the determination of pesticides in rice are also reported herein.

2. Experimental

2.1 Reagents

Diazinon, parathion-methyl and chlorpyrifos were purchased from Sigma-Aldrich (St. Louis, MO, USA). All the other chemicals and gases were of analytical grade and were purchased from commercial sources.

2.2 Apparatus

A gas chromatograph/mass spectrometer (GC 6890 equipped with 5973 mass selective detector; Hewlett-Packard, Avondale, PA, USA) was used in this study. A novel type of Hadamard-injector was prepared in our laboratory; it can be controlled via a personal computer through a PCI 6221 device (National Instruments, USA), according to a series of Hadamard codes. A commercial supercritical fluid extractor (CO_2 pump, PU-1580-CO_2/HPLC pump, PU-2080; JASCO, Japan) was used to the extract the spiked pesticides. The HT-GC chromatograms were calculated using the LabVIEW program.

3. Methodology

3.1 Hadamard transform (HT)

The Hadamard transform (HT) technique has been applied in a variety of fields, including time-of-flight mass spectrometry (Brock *et al*., 1998; Fernández *et al*., 2002; Trapp *et al*., 2004; Fernández *et al*., 2001), Raman spectrometry (Treado *et al*., 1990; DeVerse *et al*., 2000; DeVerse *et al*., 1999), fluorescence imaging (Chen *et al*., 1995; Mei *et al*., 1996; Tang *et al*., 2002; Hassler *et al*., 2005) ion mobility spectrometry (Clowers *et al*., 2006; Szumlas *et al*., 2006), and NMR (Kubo *et al*., 1996; Feliz *et al*., 2006). In addition, the application of the cross correlation technique to chromatographic separation was first proposed by Izawa and coworkers. A Hadamard matrix on the order of n, H_n, is an $n \times n$ of +1's and -1's with the property of the scalar product of any two distinct rows being 0. Thus, H_n must satisfy the following equation,

$$H_n H_n{}^T = H_n{}^T H_n = nI_n \qquad (1)$$

where $H_n{}^T$ is the transpose of H_n and I_n is the unit matrix on the order of n. A fundamental equation of the Hadamard transformation is given by

$$[\eta] = [S] \times [C] \qquad (2)$$

where η is a series of data, i.e., the observed chromatogram, encoded by a cyclic S-matrix, S, which is the $(n-1) \times (n-1)$ matrix consisting of "zero" and "one" elements, and C is a series of data representing a chromatogram. A cyclic S-matrix on the order of $(n-1)$ is obtained by omitting the first row and column of H_n and then changing +1's to 0's and -1's to 1's. To encode the chromatogram, C, a sample and eluent are introduced into a column according to the PRBS (pseudorandom binary sequence) derived from the cyclic S-matrix. When the elements of the PRBS are "one" and "zero," sample and eluent plugs are introduced into the column, respectively. As a result, the encoded chromatogram, η, is obtained. The encoded chromatogram is decoded to the chromatogram, C, by multiplying an inverse matrix of S, S^{-1}, as follows.

$$[C] = [S]^{-1} \times [\eta] \qquad (3)$$

Consequently, the decoded chromatogram shows improvement in the S/N ratio (Fellgett advantage). In both correlation and HT methods, the key technology, based on multiple input techniques according to PRBS, is the injection device, which permits the continuous introduction of a sample. Multiple injection devices for GC have also been developed for correlation GC, in which the solenoid valve (Smit, 1970; Annino and Bullock, 1973), cylindrical slide valve (Kaljurand and Küllik, 1979), and fluidic logic gate (Annino *et al.*, 1979) were used. Conversely, in correlation LC, the input signals modulated by PRBS were generated by valve systems (Lub *et al.*, 1978; Smit *et al.*, 1980; Laeven *et al.*, 1983; Mars and Smit, 1990; Kaljurand *et al.*, 1992) and by an electrochemical concentration modulator (Engelsma *et al.*, 1990).

3.2 Hadamard-injector

A schematic drawing is shown in Figure 1. The developed Hadamard-injector permits a pressurized gas or pressurized liquid to be injected into a separation column according to a pseudorandom binary sequence (PRBS), *i.e.* a Hadamard code. In fact, it was made by
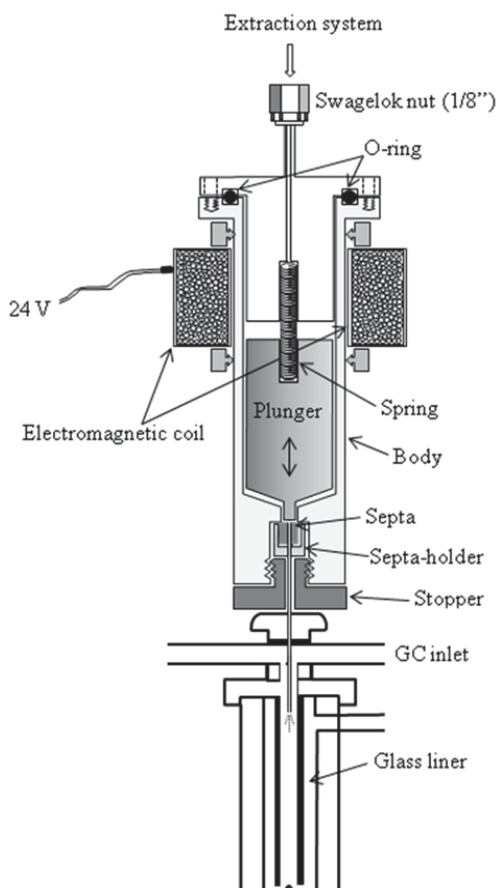

Fig. 1. A schematic drawing of the Hadamard injector used in this study.

modifying a regular pulse nozzle (Lin and Imasaka, 1993). Instead of a pinhole, which is used in general pulse nozzles, a piece of a capillary was used for the introduction of the pressurized sample solution (I.D., 50 µm; 8 cm in length). The body of the Hadamard-injector was made of brass; the plunger had a diameter of 9.5 mm and a length of 34 mm. A 24 V electromagnetic coil and the spring were removed from a solenoid valve (SMC model VX2110: 0~1.5 MPa, Japan), respectively, and used directly. A septa-BTO (Item No. 298735) was inserted into a brass holder, which was used to firmly attach the capillary and prevent gas or liquid leaks, and was sealed with a brass stopper. The Hadamard-injector can be heated and directly inserted into the GC inlet; the injection volume of the sample solution can be adjusted by changing the background pressure (nitrogen gas), the inner diameter of the capillary, the capillary length and the injection time to achieve a micro-controlled injection. During the sample injection process, a personal computer was used to rapidly turn the Hadamard-injector on and off through the PCI 6221 device, according to a series of Hadamard codes, leading to the introduction of the pressurized sample solution through the capillary into the GC column. The injection volume of the pressurized sample solution can be adjusted by changing the background pressure (nitrogen gas), the inner diameter of the capillary, capillary length, and injection time. Figure 2 shows the relationship between the injected volume and injection time based on various background pressures (A, for pressurized gas: 1.3~ 1.8Kg/cm^2; B, for pressurized liquid: 1.5 ~ 3 Kg/cm^2, respectively). Herein, the injected volume was recognized by means of a gas drainage method (Figure 2A) and by weighing the collected liquid (Figure 2B), respectively. As can be seen in Figure 2A (for pressurized gas), when the injection time was adjusted in the range of 1 ~3 s, the injection volume can be controlled from 0.3 to 4.2 µL; in Figure 2B (for a pressurized liquid), when the injection time was adjusted in the range of 0.1 ~1 s, the injection volume can be controlled from 0.04 to 0.3 µL. It should be noted that both show very good linear relationships. The RSD (related standard deviation) values of within-day and between-day were determined to 0.24 ~ 0.38% and 0.27%, respectively, indicating the stability and reproducibility of the procedure. Furthermore, the sample injection time, volume and split-ratio were investigated in detail during GC separation experiments.

4. Results and discussion

Figure 3 shows a schematic diagram of the on-line SFE/HT-GC/MS system. This system consists of a commercial SFE instrument, a commercial GC/MS, a holding tank and the Hadamard-injector. A 2.0 g sample of rice, obtained from a local supermarket, was spiked with three different pesticides (diazinon, chlorpyrifos and parathion-methyl, 30 µg each). The rice sample had first been subjected to a typical GC/MS method to confirm the absence of pesticide contaminants. The extraction liquid was 1.5 mL of acetonitrile. A 0.8 g quantity of glass beads was also placed in the holding tank to suppress bubbling. The CO_2 pressure was set at 20.3 MPa so as to extract the pesticides at a flow rate at 1 mL/min (oven temperature, 50 °C). After adding 15 mL of supercritical CO_2 fluid, the liquid was slowly passed through the spiked rice sample at a constant rate, the extracts were passed through a filter (0.45 µm) and then directly injected into the GC column by a personal computer, which turned the Hadamard-injector on and off, quickly, based on the Hadamard codes. The optimized conditions were a background pressure of 3 Kg/cm^2 and an injection time of 0.2 s. The injection volume was estimated to be ~ 66 nL for a single injection.
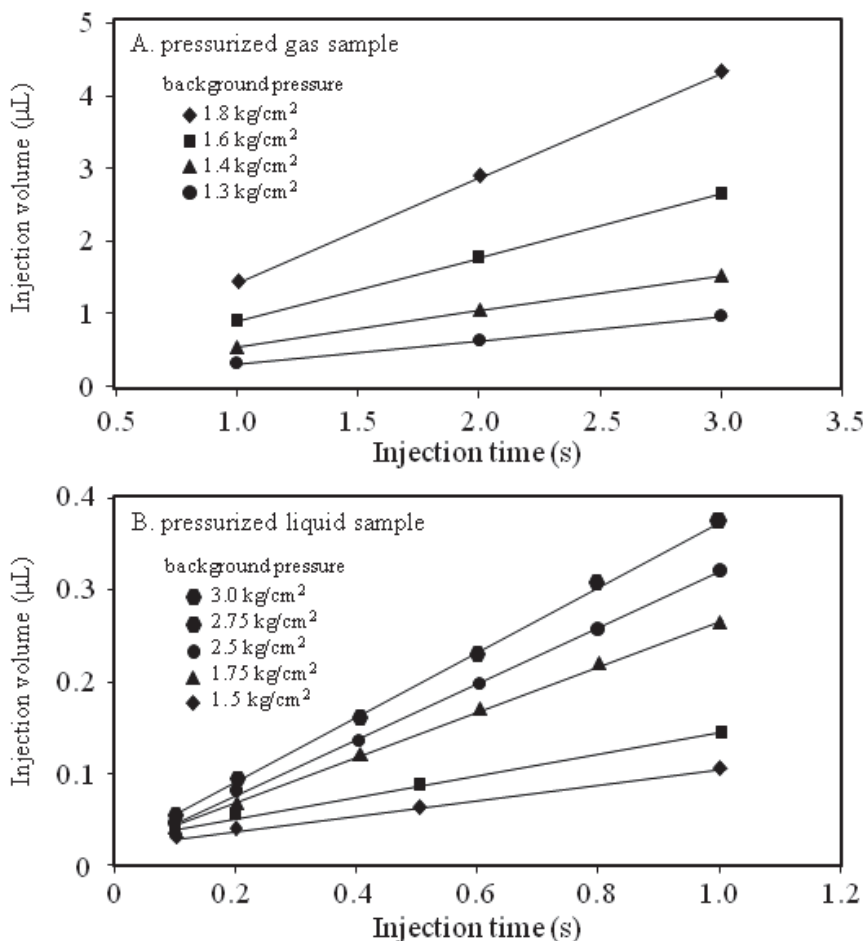
Fig. 2. Relationships between injected volume and injection time based on various background pressures (A, pressurized gas: 1.3 ~ 1.8 Kg/cm^2; B, pressurized liquid: 1.5 ~ 3 Kg/cm^2, respectively).

Figure 4 shows typical GC/MS chromatograms for parathion-methyl standard by means of single injection (frame A) and Hadamard injection (frame B). The concentration level was 20 μg/1 mL acetonitrile. In the case of single injection, injection volume was 66 nL (absolute amount, 1.3 ng). The findings show that the S/N ratio of the chromatogram was relatively poor in frame A. However, under the same experimental conditions, when the Hadamard injection was performed (as shown in frame B; matrix order, n = 255), and each injection volume was still 66 nL, the S/N ratio was dramatically improved. The inset in frame B shows the details of raw data before the inverse Hadamard transformation (chromatogram a, whole chromatogram; chromatogram b, portion chromatogram of n = 127 ~ 238) and the Hadamard code (chromatogram c, n = 127 ~ 238). As can be seen, chromatograms b and c are quite matched, and for this reason, the S/N ratio improved as excepted.
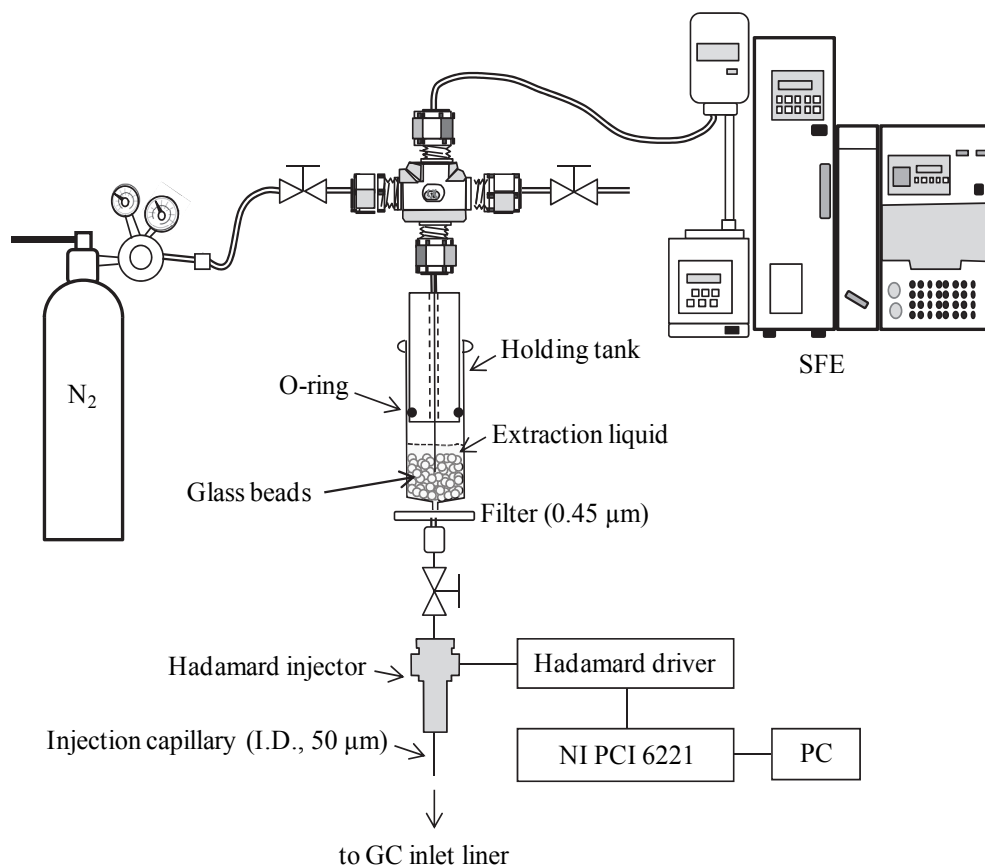
Fig. 3. A schematic diagram of the on-line SFE/HT-GC/MS system.

When analyzing a mixture of different pesticides, the use of Hadamard transform is also helpful to improve the S/N ratio. In this case, three types of pesticides (diazinon, parathion-methyl and chlorpyrifos) were spiked in the sample rice. Figure 5 shows typical HT-GC/MS chromatograms of the on-line SFE extracts from the spiked rice sample. Herein, the SIM mode was used (ion peaks at m/z = 125, 137 and 199 were selected for monitoring). Chromatograms a and b show the results obtained for a single injection and a Hadamard injection (matrix order, n = 255), respectively. As can be seen, the S/N ratio is again substantially improved. The detected peaks are also completely consistent with the theoretical prediction. Table 1 shows the relationship between the enhancement in S/N ratios and mass conditions for analysis based on on-line supercritical fluid extraction/HT-GC/MS methods (SIM mode was used; m/z = 125, 137, 199 for diazinon, chlorpyrifos and parathion-methyl, respectively). The results indicate that the on-line SFE/Hadamard-injector described herein also permits precise multiple injections and that it can be used for the determination of actual samples.
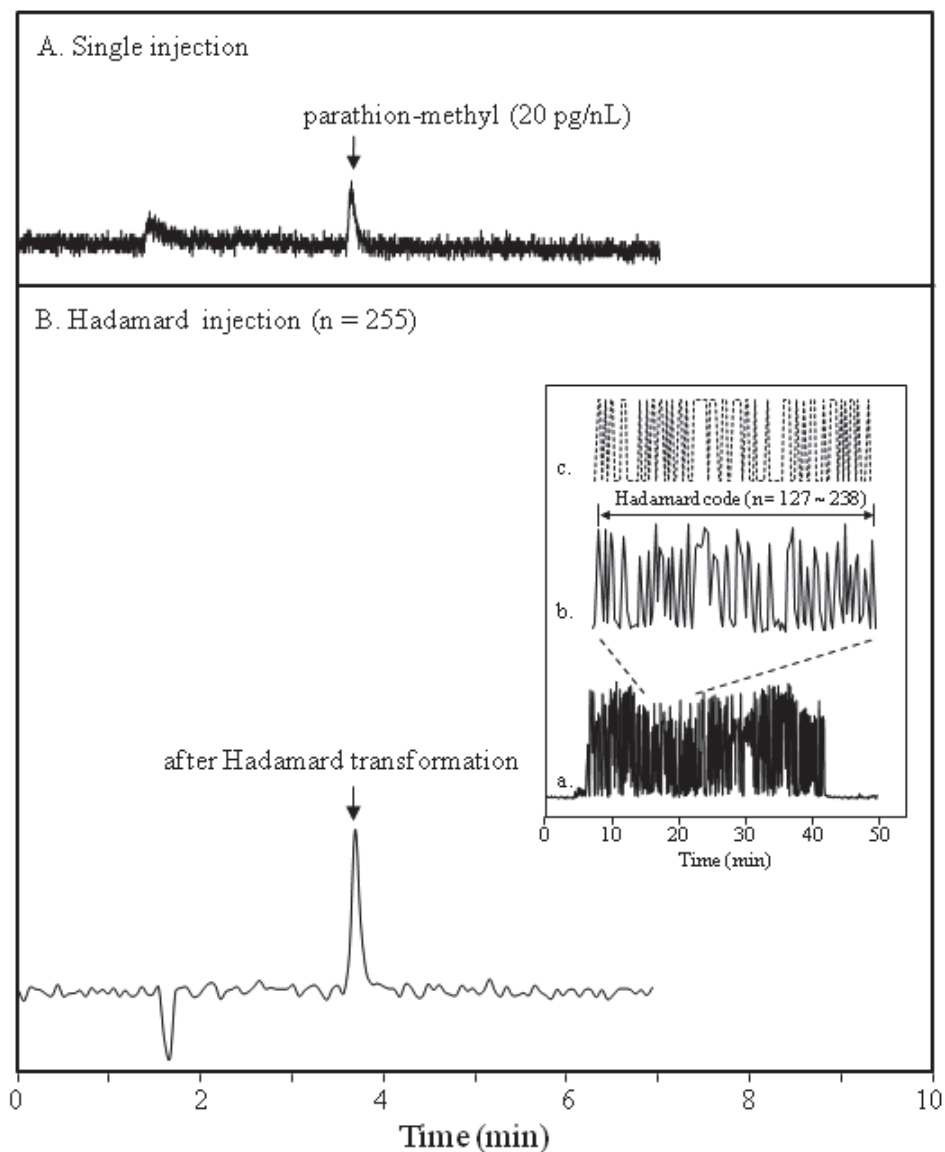
Fig. 4. Typical GC/MS chromatograms for parathion-methyl standard; concentration level, 20 μg/1 mL acetonitrile. In frame A, chromatogram was obtained by single injection (injected volume, 66 nL; absolute amount, 1.3 ng). In frame B, chromatogram was obtained by Hadamard injection (Hadamard matrix, n = 255; each injection volume, 66 nL; total injection volume, 16.8 μL). The inset in frame B shows the details of raw data before the inverse Hadamard transformation (chromatogram a, whole chromatogram; chromatogram b, portion chromatogram of n = 127 ~ 238) and the Hadamard code (chromatogram c, n = 127 ~ 238).
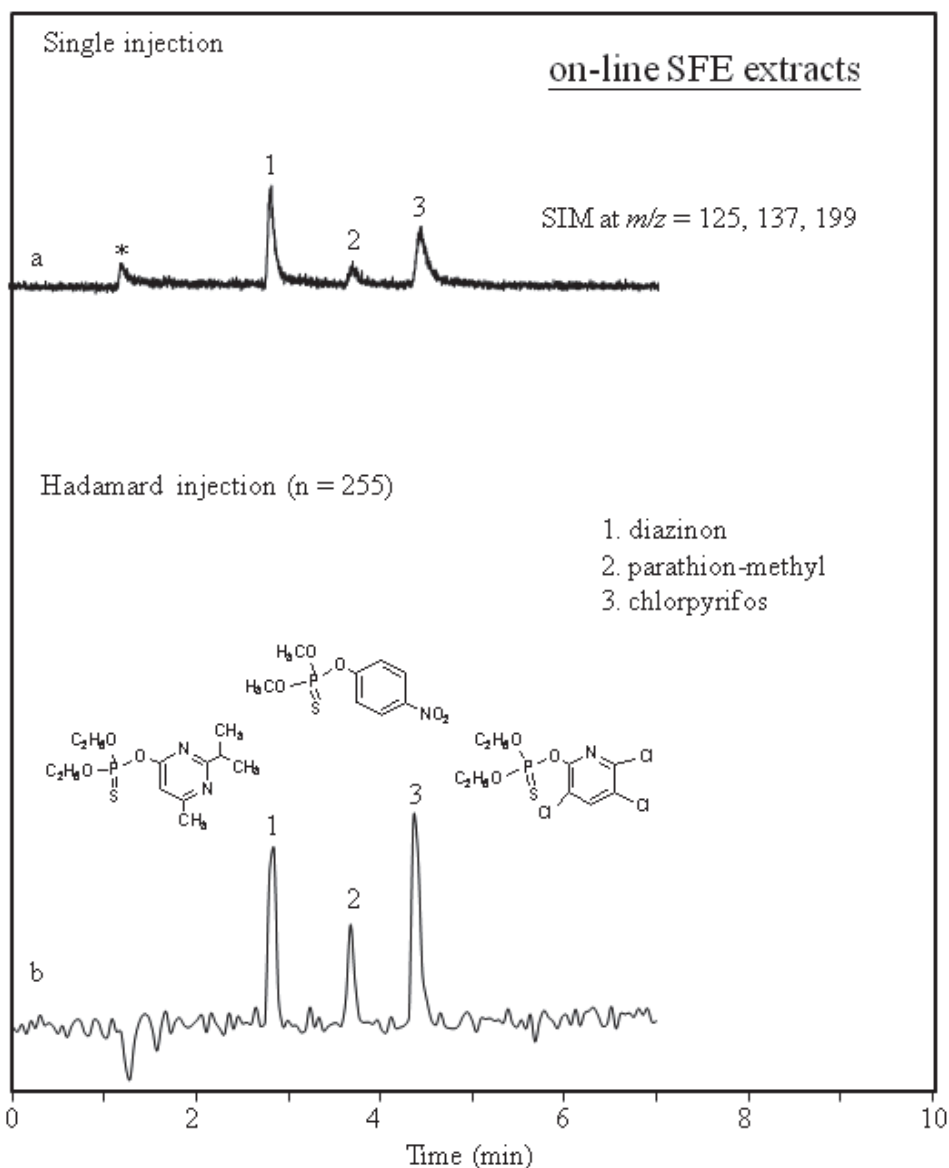
Fig. 5. Typical GC/MS chromatograms of the on-line SFE extracts based on the SIM mode. Chromatograms a and b show single-injection and Hadamard injection (order of matrix, 255), respectively. Diazinon, chlorpyrifos and parathion-methyl (30 μg of each) were spiked to 2.0 g rice. Inset, the raw data shown before inverse Hadamard transformation. The solvent peak is indicated by "*".

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Matrix order	Enhancement of S/N ratio
	theoretical
255	8.02
	observed
diazinon	6.8
chlorpyrifos	4.3
parathion-methyl	7.6

The enhancement of the S/N ratio was calculated as the ratio of S/N values obtained in the chromatograms, measured by HT-GC/MS and a single injection method.

Table 1. Relationship between the enhancement in S/N ratios and mass conditions for analysis based on on-line supercritical fluid extraction/HT-GC/MS methods (SIM mode was used; m/z = 125, 137, 199 for diazinon, chlorpyrifos and parathion-methyl, respectively).

5. Conclusion

In this study, we developed novel Hadamard-injectors coupled with sample collection systems. The SFE system was successfully interfaced with the Hadamard-injector and the extracts were successfully collected. The utility of the method was demonstrated using some representative pesticides as model compounds. The device permitted continuous and precise sample injections in HT-GC/MS, resulting in a substantial improvement in S/N ratios through the application of the Hadamard transformation. The enhancement factors for the S/N ratios were matched with the theoretical values. Thus, this method has a variety of applications and could potentially be used in practical trace analysis.

6. Acknowledgment

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