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Gas chromatographic determination of glutaraldehyde in the workplace atmosphere after derivatization with *O*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine on a solid-phase microextraction fibre

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Abstract

Glutaraldehyde is used primarily in hospital environments for the disinfection of various instruments (e.g., endoscopes). We describe in this paper the measurement of glutaraldehyde in a hospital environment using solid-phase microextraction. The method includes, prior to sampling, the adsorption of *O*-(2,3,4,5,6-pentafluorobenzyl)hydroxylamine on to the fibre (with polydimethylsiloxane–divinylbenzene). The fibre is then exposed to air, after which desorption is performed in the GC injection port. This process results in the formation of a stable derivative of the glutaraldehyde that is suitable for chromatographic purposes and detectable with classical detection methods, such as flame ionisation and electron-capture detection. We demonstrate that the procedure of adsorption, thermal desorption and derivatization is robust and reproducible. We were able to detect concentrations of 60 $\mu g/m^3$ (10 s sampling) or 6 $\mu g/m^3$ (120 s sampling) by electron-capture detection, and 80 $\mu g/m^3$ (120 s sampling) by flame ionisation detection. We compared our method to currently existing methods of glutaraldehyde measurement and highlighted several important advantages of the method.

Keywords: Air analysis; Derivatization, GC; Solid-phase microextraction; Glutaraldehyde; Aldehydes; Pentafluorobenzylhydroxylamine

1. Introduction

Glutaraldehyde in aqueous solution (2%) is commonly used in hospital environments for the sterilization and disinfection of various types of endoscopic equipment [1]. Exposure to glutaraldehyde usually occurs via the lungs and skin, and generally evokes irritation responses in the conjunctive membranes. These include contact dermatitis [2,3], bronchial asthma [4–6], and allergic reactions in the eyes [7]. In addition, several mutagenic and fetotoxic effects have been experimentally demonstrated, while in-

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vestigation of carcinogenic effects proved negative [8].

The American Conference of Governmental Industrial Hygienists (ACGIH) proposes a threshold limit value-ceiling (TLV-C) of 0.05 ppm of glutaraldehyde vapour in work environments (corresponding to 200 $\mu g/m^3$). This concentration is not to be exceeded during any part of the working exposure. In correctly measuring the TLV-C in work environments, the ACGIH further advises (when possible) instantaneous sampling or sampling not exceeding 15 min in duration [9]. This has resulted in the development of various sampling and monitoring methods for glutaraldehyde in air. These, for the most part, are based on solid substrate sampling, and may often involve the use of derivatizing agents [10–16]. Several authors, for example, have proposed the use of the passive sampler Tenax TA which is impregnated with *O*-(2,3,4,5,6-pentafluorobenzyl)-hydroxylamine (PFBHA) hydrochloride [16]. Air sampling is performed by passive diffusion or by aspiration over the adsorbent at flow-rates of between 0.005 and 2 l/min for durations of less than 15 min. At the end of the sampling period, the glutaraldehyde or its derivative are then eluted from the adsorbent and analysed by high-performance liquid chromatography (HPLC)–UV [12,13,15] or by gas chromatography (GC) with flame ionisation detection (FID), electron-capture detection (ECD) or mass spectrometry (MS) [10,11,14,16]. A disadvantage of these methods, however, is that they generally require relatively long sampling periods. Consequently, several alternative procedures have been developed that permit the instantaneous sampling of glutaraldehyde in air. These are based on equipment that continually sample the air, concurrently measuring glutaraldehyde concentrations with either IR detectors (e.g., the photoacoustic multigas monitor, with detection limit 890 $\mu g/m^3$) or electrochemical fuel cells (with detection limit 120 $\mu g/m^3$) [14].

More recently, the use of solid-phase microextraction (SPME) has been proposed for the measurement of various substances (e.g., solvents) dispersed in air. An important advantage of this technique is that the fibre can be used for both short (from 10 s to 5 min) [17] and long sampling periods (from 15 min to 16 h) [18]. For example, Martos and Pawliszyn used SPME, with PFBHA as derivatizing agent on the fibre, to measure the levels of formaldehyde in air [19]. In a similar manner, we have developed an analytical method using SPME and derivatization with the same derivatizing agent on the fibre that allows for the determination of low environmental concentrations of glutaraldehyde (6–20 $\mu g/m^3$) with sampling periods of less than 15 min. In this paper we describe our procedure and compare it to other existing analytical methods. Furthermore, we discuss the experimental application of SPME to the monitoring of environmental levels of glutaraldehyde.

2. Experimental

2.1. Materials

We used Supelco (Sigma–Aldrich, Milan, Italy) polydimethylsiloxane–divinylbenzene (PDMS–DVB) SPME fibres with a phase thickness of 65 μm. Analytical-grade acetone, PFBHA·HCl (purity> 99%), and aqueous solutions of glutaraldehyde (purity~25%, Grade II) were purchased from Fluka (Sigma–Aldrich). Given the extreme ease with which aldehydes are polymerised, the solution at 25% was titrated with 1.13 *M* sodium sulfite (Sigma–Aldrich), using the method proposed by the NIOSH [12]. Two section Pyrex containers (6×70 mm, 4.0 mm I.D.) containing silica gel (150 mg front and 75 mg back, 20–40 mesh) were obtained from SKC (Superchrom, Milan, Italy). 25 l Tedlar bags (45.7×61 cm), provided with a valve (type PP with rings) and a perforated PTFE-silicone septum were also procured from SKC. Deionised water was obtained via a Milli-Q apparatus (Millipore, Milan, Italy).

2.2. Methods

The following sampling methods were compared:

(1) SPME with PDMS–DVB fibre. The fibre was exposed for 30 s in the headspace of a PTFE-capped 4 ml amber vial containing 1 ml of PFBHA in aqueous solution (17 mg/ml) and agitated at 1800 rpm by a magnetic stirrer. Subsequent sampling of environmental glutaraldehyde levels was performed by extracting the entire fibre (1 cm) from its protec-

tive needle and exposing it in the air for a short period (10 s and 2 min).

(2) Adsorption of glutaraldehyde in air on to a silica gel with a personal air sampler (Gilian Instrument, TCRTECORA, Milan, Italy). The flow-rate was maintained at 1.00±0.05 l/min for 15 min. After sampling the two sections of the glass containers containing the silica gel were eluted separately with 1 ml of acetone.

(3) Continuous sampling and analysis using the photoacoustic multigas monitor (Model 1312/5, Innova Air Tech Instrument, D.S.S., Padova, Italy). Calibration of optic filters (UA 0986, centre wavelength 3.6 μm, centre wave number 2800 cm^{-1}, detection limit at 20 °C and 1 atm pressure and sample integration time of 5 s is 0.2 ppm; 1 in.=2.54 cm; 1 atm=101 325 Pa) for glutaraldehyde was performed by an Innova Air Tech Instrument (Dk-2750, Ballerrup, Denmark).

2.3. Instruments and chromatographic conditions

In the first method, the analysis of the glutaraldehyde derivative bis-PFB-oxime was performed using a Varian gas chromatograph Model CP-3800 (Varian Italia, Turin, Italy) equipped with an electronic pressure control for carrier gas and an FID and a ^{63}Ni ECD system (used alternatively). For analyses in method 2, only the FID system (of the same GC) was used. A fused-silica SPB-5 (5% phenyl–95% methylsiloxane), 30 m×0.25 mm I.D., 1 μm film thickness capillary column from Supelco (Sigma–Aldrich) was used. The operating conditions for the various methods are detailed in Table 1. The retention times for mono- and bis-PFB-oxime derivatives were 17.3 and 23.8 min, respectively.

The identity of the glutaraldehyde bis-PFB-oxime, derivative as well as its mono-PFB-oxime derivative, was confirmed by mass spectrometry using a GC–MS instrument from Agilent Technologies (Cernusco, Milan, Italy). This was composed of a HP 6890 gas chromatograph and a HP 5973 mass-selective detector. The fused-silica capillary column used was a Supelco MDN-5S (30 m×0.25 mm I.D., 0.25 μm film thickness), while the carrier gas was helium at a constant flow of 1.2 ml/min. The oven temperature program was as follows: 50 °C held for 1 min, then at 10 °C/min to 270 °C held for 15 min. Injector and transfer line temperature was 270 °C. Mass spectra were obtained in the electron impact ionisation (EI) mode (70 eV, source temperature 200 °C), and in the negative chemical ionisation (CI) mode (isobutane reagent gas, source temperature 150 °C).

Table 1
Operating conditions for three analytical methods of glutaraldehyde sampling

	SPME	Silica gel
Injection technique	Splitless for FID; split for ECD (split ratio 1:10)	Split (split ratio 1:2)
Injector liner; temperature	0.75 mm I.D.; 270 °C	4 mm I.D.; 185 °C
Desorption time/injected volume	10 min	2 μl acetone
Carrier gas	Helium at 2 ml/min (constant flow)	Helium at 2 ml/min (constant flow)
Temperature program	50 °C held for 1 min, at 10 °C/min to 270 °C, hold for 15 min	50 °C held for 1 min, at 10 °C/min to 200 °C, hold for 2 min
Detection method and temperature	FID, 270 °C, or ECD, 300 °C	FID, 200 °C
Gas make-up for ECD	Ar–CH_4 (5%, v/v, CH_4), 30±1.0 ml/min	
Gas for FID	Nitrogen, 30.0±1.0 ml/min Air, 300±10 ml/min H_2, 30.0±0.8 ml/min	Nitrogen, 30.0±1.0 ml/min Air, 300±10 ml/min H_2, 30.0±0.8 ml/min

2.4. Calibration system

When determining the environmental concentrations of organic substances, particular importance must be paid to the calibration of the sampling and analysis system. The calibration of the fibre, in the SPME–GC technique, can be performed in two ways:

(a) The first method involves the calculation of the constant K (at a pre-stabilised temperature), given by the quantity of the analyte adsorbed by the fibre in comparison to the concentration of the same analyte in air [20]. The absolute quantity of the sampled substance is then calculated on the basis of comparison with standard solutions of known concentrations injected into the GC system. An alternative determination of K is by the linear temperature-programmed retention index (LT-PRI) [21].

(b) The second method entails the generation of gaseous standard mixtures of the analyte of known concentrations. As standard and sample are subjected to the same operating conditions, calibration becomes an integrated part of the analytical procedure [22]. When the GC–SPME–detection results are in a linear range, the environmental concentration is calculated from the gaseous standard curve. Several authors [23] have prepared gaseous mixtures of known concentrations in 500 or 1000 ml glass sample bulbs, injecting dilute solvent solutions in methanol or dichloromethane at known concentrations. The fibre is then exposed inside the container, which is heated (e.g., 100 °C for 10 min) and cooled to room temperature beforehand, for a set period. Alternatively, other authors have used a dynamic calibration system in which known concentrations (held constant over time) of analyte are generated by permeation tubes [24] or syringe pumps [25].

The twofold necessity of calibrating the fibre, and comparing precision and reproducibility with the other two sampling and analysis methods, forced us to eliminate the use of glass sample bulbs. Instead, we developed a more rapid and economical system based on permeation tubes and syringe pumps as utilised by others [24,25]. In preparing air samples containing known concentrations of glutaraldehyde (and representing as closely as possible actual air samples), we made use of the system developed by Russo and Que Hee [26] with minor modifications (Fig. 1).

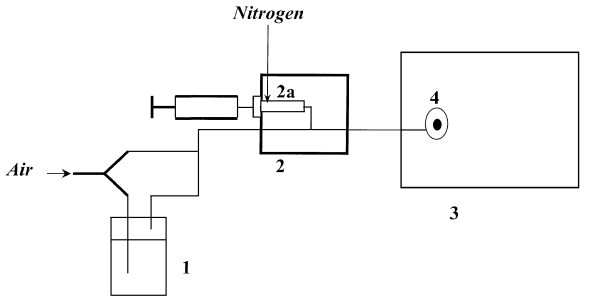

Fig. 1. The apparatus for generation of gaseous standard mixtures: (1) humidifier, (2) thermostatic block with injector port (2a), (3) Tedlar bag, (4) valve. See text for details.

When operating, a volume corresponding to 5 μl of aqueous glutaraldehyde solution of known concentration is injected by means of a Hamilton 10 μl gas-tight syringe (Superchrom, Milan, Italy) into an injector port at 200 °C (2a in Fig. 1) (obtained from a Perkin-Elmer GC, Model Sigma 3B, and equipped with a 4 mm I.D.×6 mm O.D. glass liner), installed in a thermostatic block maintained at 60 °C (2 in Fig. 1). The absence of metallic surfaces at high temperature (present in the Russo and Que Hee apparatus) could limit the observed partial decomposition of glutaraldehyde in the injection–vaporisation part [10]. The glutaraldehyde vapours formed are transported by nitrogen (flow-rate 0.10±0.01 l/min) and mixed with decarbonated dry air (flow-rate 2.4±0.2 l/min, measured by a calibrate Rota Rotameter Model Rota L 6,3/250) from the humidifier (1 in Fig. 1). This gaseous mixture, of known concentration, is transferred through a thermostated (50 °C) Pyrex tube and then collected in a 25 l Tedlar bag (3 in Fig. 1) equipped with a valve (type PP with rings) with a perforated PTFE-silicone septum (4 in Fig. 1). The concentration of water vapour produced by the humidifier (1 in Fig. 1) is measured before, by connecting (in place of the tedlar bags) a 1386 ml glass flask containing a probe for measurement of dew point temperature ($T_{\text{dew point}}$) of the photoacoustic multigas monitor. Relative humidity (RH) was obtained from the Merck Index table after measurement of the temperature at dew point and the temperature of air. Under the experimental conditions detailed above, a relative humidity of 54% and a temperature of 25 °C were obtained at equilibrium. No problems associated with the decomposition of

the glutaraldehyde in the thermostatic block were encountered.

For preparation of air samples on which to test the three analytical methods, we prepared nine standard solutions of glutaraldehyde each day (0.031, 0.062, 0.312, 0.625, 1.25, 2.5, 5.0, 10.0 and 20.0 μg/μl) in deionised water. A 5-μl volume of each solution was injected into the above-described system. For each Tedlar bag the concentration of glutaraldehyde was determined, first with the continual sampling equipment for five readings (approximately 3 l sampled), followed by the flasks containing silica gel, aspirating (by means of a pump) at a flow-rate of 1.00±0.05 l/min for 15 min. Finally, after having perforated the septum, the SPME fibre was exposed and maintained in contact with the air within the bag for various predetermined times.

3. Results

The concentrations of glutaraldehyde obtained by the three sampling and analysis systems (silica gel, IR monitor and SPME) are presented in Table 2. In general, all three methods produced values in close agreement with those theoretically predicted. Moreover, SPME, especially when using FID, demonstrated excellent sensitivity when compared with the other two methods. The concentration interval measured is comparable to that obtained with silica gel, but is achieved with SPME in much shorter sampling periods.

We evaluated the limit of quantification (LOQ) and the linearity of our method under various operative conditions, sampling periods and with the two detector types. We choose a signal having a signal-to-noise ratio higher than 5 and a peak area in the linear range of the calibration curve as the LOQ. When exposing the fibre for 10 s, the SPME–ECD technique had an LOQ of 62.5 $\mu g/m^3$, while fibre exposure for 2 min produced an LOQ of 5.6 $\mu g/m^3$. These compared well with theoretical predictions. When using the SPME–FID system it was necessary to sample for at least 2 min, yielding an LOQ of 80 $\mu g/m^3$. Regarding the linearity of the method, linearity in SPME–ECD occurred from 62.5 to 1000 $\mu m/m^3$ for sampling of 10 s, and from 6.2 to 250 $\mu m/m^3$ for 2 min sampling. In SPME–FID, linearity (linear regression: $y=6.2\cdot10^{-6}x+68\,161$; $R^2=0.9951$) occurred in the concentration interval of 125 to 4000 $\mu g/m^3$.

We further evaluated the time necessary to reach the equilibrium state exposing the fibre for varying time periods in two Tedlar bags containing 1250 $\mu g/m^3$ and 125 $\mu g/m^3$ glutaraldehyde, respectively. Our results obtained on six repeated samples demonstrate that equilibrium (saturation) occurs after 1200 s at a concentration of 1250 $\mu g/m^3$, with loss of linearity occurring at approximately 360 s. In contrast, at a concentration of 125 $\mu g/m^3$, excellent

Table 2
Experimental comparisons of three systems for the analysis of glutaraldehyde

Standard solutions*	Concentration ($\mu g/m^3$)					
	Expected	Silica gel ($n=5$), mean±SD	IR ($n=5$), mean±SD	SPME ($n=5$)		
				FID 2 min, mean±SD	ECD 2 min, mean±SD	ECD 10 s, mean±SD
0.031	6.2	ND	ND	ND	6±1	ND
0.062	12.5	ND	ND	ND	19±2	ND
0.312	62.5	58±11	ND	ND	60±3	58±10
0.625	125.0	120±17	ND	118±12	120±11	100±12
1.250	250.0	240±26	ND	245±18	242±21	210±20
2.500	500.0	475±39	ND	490±31		450±40
5.000	1000.0	985±102	1037±50	990±79		960±83
10.000	2000.0	1900±271	2012±70	1950±153		
20.000	4000.0	3920±357	4036±160	3900±304		

*: 5 μl injected in the apparatus of Fig. 1.
ND=not measurable.

linearity (R^2=0.9931) occurred between sampling times 120 and 4800 s.

The derivatizing agent adsorbed into the SPME fibre remains stable for at least 24 h; in GC–FID we obtained identical results from the same bag sampling with a fibre exposed to PFBHA vapours 24 h before, and with a fibre exposed to PFBHA immediately before the sampling.

We applied our method to five working rooms in a hospital in Florence, comparing it with the IR and silica gel methods, used simultaneously. The glutaraldehyde levels in air were determined during two different operations: the first, during the emptying or the filling of the basin to renew the glutaraldehyde solution (samples A 1 and A 2, Table 3), and, the second, during the short opening time to introduce the endoscopes and other tools into the basin (sample B, Table 3). In the second case, due to the low concentration of glutaraldehyde in air, no data were obtained using the IR monitor (levels always lower than the detection limit of the instrument). The data obtained from silica gel (15 min sampling) and SPME–ECD (2 min sampling) were compared: a good agreement was noted between the values. Because of the different sampling times of the two methods, in these preliminary samples the two methods run simultaneously for the first 2 min of sampling only.

The samples of the A series were obtained while large volumes (approximately 10 l) of glutaraldehyde solution were transferred from tanks to basins or from basins to waste, in a time ranging from 30 s to 2 min depending from the operators. In this case it was possible to compare the results from the IR monitor with the ones from SPME–FID (2 min sampling) and SPME–ECD (10 s sampling). The two methods were able to record the peak of glutaraldehyde concentration in workplace air: the results were in good agreement in this case, too. As shown in the column of Table 3 referring to silica gel, this technique is not suitable for recording the maximum ''instantaneous'' concentration of glutaraldehyde: the value expressed by this method represents the average concentration of glutaraldehyde after 15 min of sampling. By means of IR monitoring, we appreciate a relatively rapid decrease of its concentration after the completion of the decanting of the solution.

Both SPME and IR were able to detect the elevated level of glutaraldehyde reached for a short time in the small rooms in which sterilisation was performed. These rooms are characterised by a minimum, if not absent, air velocity and they are lacking in hoods or exhaust fans, in which it is possible to carry out the operations of filling or emptying the bowls containing the glutaraldehyde solution.

As pointed out both by IR and by SPME, the

Table 3
Glutaraldehyde concentration (mg/m^3) measured in five different hospital rooms in which sterilization with glutaraldehyde is used, obtained with three different methods

Working operation	IR monitor	SPME–FID, 2 min[a]	SPME–ECD		Silica gel 15 min[a]
			10 s[a]	2 min[a]	
A 1	0.92[b]	0.80	0.85	–	0.205
A 2	1.38[b]	1.42	1.24	–	0.383
A 2	1.32[b]	1.23	1.12	–	0.324
A 2	2.01[b]	2.32	–	–	0.458
A 2	1.71[b]	1.89	–	–	0.380
A 2	1.10[b]	1.12	–	–	0.240
B	N.D.	–	–	0.075	0.080
B	N.D.	–	–	0.028	0.035
B	N.D.	–	–	0.049	0.028
B	N.D.	–	–	0.018	0.025
B	N.D.	–	–	0.055	0.030

N.D.=Not detected. The measurements were performed during two principal working operations: emptying (A 1) or filling (A 2) of the basins with glutaraldehyde solution, and immersion or drawing of endoscopes in the basins (B).

[a] Sampling time.

[b] Mean value from two consecutive measurement during 2 min.

TLV-C is often exceeded in these operational conditions. The good agreement between the values determined by SPME–FID (2 min sampling time) and by IR monitoring (average of two subsequent readings performed in the same 2 min of SPME sampling) shows, in our opinion, that SPME can be regarded as a good alternative to the expensive IR in TLV-C control. If using SPME–ECD, sampling frequency, with a sufficient number of fibres available, can be higher than that of IR, but the presence of an operator for SPME sampling is absolutely necessary.

4. Discussion

Our results demonstrate that the SPME technique is an excellent analytical tool for measuring environmental levels of glutaraldehyde. SPME–ECD, especially, allowed for the determination of extremely low concentrations of dispersed glutaraldehyde (as low as 6 $\mu g/m^3$) with short sampling periods, when compared to the other two methods. In general, our technique was able to detect concentrations between 10 and 100 times lower than those measured with silica gel and the photoacoustic multigas monitor. This sensitivity is a result of thermal desorption from the fibre in the GC injector ensuring complete transfer of the glutaraldehyde derivative onto the analytical column, as well as the sensitivity and specificity of the ECD system for the fluorinated derivatives of aldehydes. Furthermore, even analyses with the GC–FID system produced favourable results. We were able to detect glutaraldehyde concentrations approximately 10 times lower than those detected by the multigas monitor under an analogous sampling regime (2 min). Comparable results by silica gel were only obtained when sampling duration was much longer (15 min). An additional advantage of our technique in comparison to silica gel and other solid matrix techniques, is that sampling and analyses are always performed on the same substrate, while eliminating the use of solvents (and thus dilution effects).

The excellent reproducibility observed in the formation of the glutaraldehyde derivative allows for the use of a molecule that is highly suitable for gas chromatography. The formation of the mono-PFB derivative is only observed when glutaraldehyde concentrations are extremely high, and is thus of negligible interest in environmental monitoring.

When considering the application of the SPME technique in work environments, it is important to bear in mind that parameters such as temperature, humidity, and wind speed can influence the capacity of the fibre. Our results demonstrate that at 25 °C and an RH of 54%, the concentration values obtained with the fibre are comparable with those of the other two systems. Martos and Pawliszyn [19] using SPME sampling, and Tsai and Que Hee [16] using passive a sampler for aldehydes, demonstrated that temperature variations of up to 5 °C have no influence on oxime quantity adsorbed onto the fibre. In addition, they observed no significant differences between sampling in static (still air) and dynamic (moving air) environments, or between fibres originating from different batches. In contrast, humidity has been demonstrated to play a role in analyte adsorption. Martos and Pawliszyn [25] showed that a decrease of 10% in the mass of analyte adsorbed occurs when the RH is greater than 90%. Realistically, humidity at such levels in work environments is unlikely, and thus places no restriction on glutaraldehyde monitoring.

The only problem that was encountered in the use of our SPME was saturation of the ECD system at concentrations of the derivatives over 1000 $\mu g/m^3$ for 10 s sampling, and 250 $\mu g/m^3$ for 2 min sampling. This problem can be resolved, however, in one of the following ways: (a) by working with FID only; though detection limits are lower than ECD, this method is sufficient for the monitoring of environments with short sampling duration; (b) by reducing the exposure time of the fibre in air (e.g., 10 s); (c) by connecting a column with two detectors and a Y-connector. This would further extend the concentration interval measurable with SPME.

5. Conclusions

Starting from the work of Martos and Pawliszyn [19], we have optimised an analytical method for the determination and measurement of glutaraldehyde in work environments that is robust, sensitive, and, above all, simple. Our results demonstrate that it is

suitable for use in the work environment. The characteristics of the method further satisfy all analytical requirements that are necessary when the protection of health in the work environment is involved. The sensitivity attained permits the evaluation of glutaraldehyde concentrations with extremely reduced sampling periods (as low as 20 s), producing an instantaneous measurement of glutaraldehyde levels. Relatively longer (2 min) exposure of the SPME fibre still allows for quantitative measurements that satisfy ACGIH guidelines. Despite the fact that continuous-sampling and analysis equipment allows for continual recording of glutaraldehyde levels, the low sensitivity (890 $\mu g/m^3$), interference by other compounds present in air (e.g., alcohols) and high costs, limit the use of such equipment in the monitoring of glutaraldehyde.

With FID, even though detection limits are generally inferior to analyses by silica gel, one can still perform efficient monitoring and with much lower sampling times. An additional advantage of SPME that is worth noting, is that, in comparison to other methods, SPME has reduced analytical costs and is easily applicable. Additionally, the absence of any solvents in the analytical procedure reduces health risks and environmental contamination [27]. The robustness of the fibre, combined with cleaning of the air sample, means that more than 200 analyses can be performed with each fibre. The excellent reproducibility of production batches of the fibre ensures that results obtained by each fibre can be compared. In conclusion, an advantage that will undoubtedly prove to have practical benefits, is the stability of derivatizing agents and glutaraldehyde derivatives on the fibre. This means that analyses do not need to be performed immediately after sampling of the environment.

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