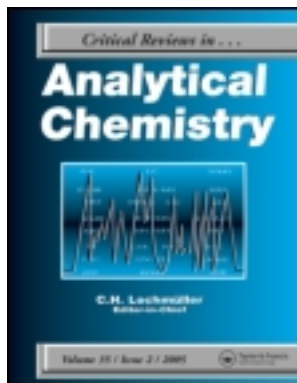


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Mobile Systems (Portable, Handheld, Transportable) for Monitoring Air Pollution

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The monitoring and analysis of atmospheric air pollutants is a rapidly developing branch of analytical chemistry. The in situ analysis of atmospheric air quality using mobile instrumentation is becoming routine. The article provides information on devices used in various kinds of mobile laboratories. It reviews the portable gas chromatographs and handheld devices used for detecting and determining specific harmful substances in ambient air. Innovative approaches in analytical instrumentation that can be used in air monitoring are presented, as are future trends in the field of mobile air monitoring systems.

Keywords air quality, monitoring of atmospheric pollution, mobile laboratory, mobile instruments, portable gas chromatograph

INTRODUCTION

The substance recognized as the first air pollutant resulting from human actions was the smoke rising from a fire (Folinsbee, 1992): it was intended to scare off wild animals. With the passage of time, humans began to add various things to fire, like feathers or sulfur, which made the smoke thicker and more effective as a deterrent. These measures led to further pollutants, like sulfur dioxide, entering the atmosphere.

The first mention of a fatality resulting from air pollution comes from ancient times: Pliny the Elder died after inhaling volcanic fumes (Bartra et al., 2007). Even though people were becoming aware of the deleterious influence on their health of chemical compounds present in smoke and dust, very little attention was given to this question for hundreds of years. It was not until the 20th century that it started to be treated as a serious problem. In London in 1952, a particular combination of atmospheric conditions (almost still air, low temperature, high humidity, thick fog, and the heavy discharge of pollutants, mainly dust and sulfur oxides) from point sources (factories and households) produced the atmospheric phenomenon known as smog. Because Londoners heated their homes with rather poor quality coal (containing a large amount of sulfur), considerable quantities of sulfur oxides were released into the air as a result of its combustion (approximately 2000 $\mu\text{g/day}$) (Folinsbee, 1992; Bartra et al., 2007; Brunekreef, 2010). These reacted with the droplets of water dispersed in the air to form sulfuric acid (H_2SO_4). It is estimated that the smog that formed then had a pH

of less than 2 (Kokkola et al., 2003). As a result of exposure to this mixture of sulfuric acid and dust in the air, several thousand Londoners perished (and a few thousand more following complications) (Folinsbee, 1992; Bartra et al., 2007; Brunekreef, 2010).

After these events, legal regulations began to be put in place to prevent such a tragedy ever happening again. In the second half of the 20th century industry, power stations and motor vehicles began to be monitored for pollutant emissions, measures that led to a substantial reduction in the levels of SO_2 and CO in atmospheric air (Brunekreef, 2010).

Nevertheless, air pollution continues to exist and is a serious hazard to human health, particularly in urban agglomerations such as Beijing, Athens, Mexico City, São Paulo, Mumbai, and Shanghai (Curtis et al., 2006). Nowadays large cities are struggling with a new type of smog—photochemical smog, a type of pollution first observed in Los Angeles (Dimitriadis, 1997). Certain conditions are needed for it to form (Lu and Turco, 1996):

- Large amounts of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) emitted during the combustion of liquid fuels,
- Stagnant air—minimal air circulation, or none at all,
- Very high insolation and a high air temperature ($\sim 25^\circ\text{C}$).

One of the constituents of photochemical smog is tropospheric ozone (O_3). A secondary pollutant, it is not emitted directly into the air but forms as a result of photochemical reactions, whose precursors are NO_x and VOCs. The photolysis of

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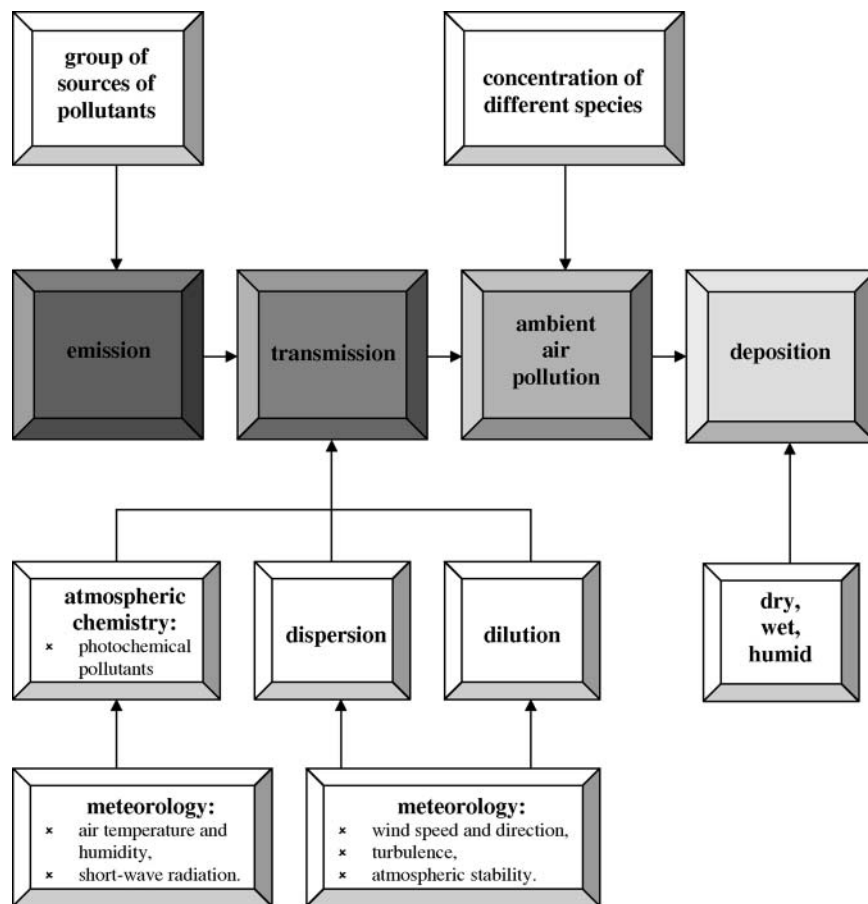
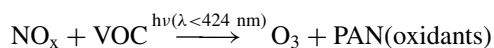


FIG. 1. Transport pathways of contaminants in the atmosphere (Mayer, 1999).

NO_2 in the presence of intense solar radiation produces atomic oxygen (O), which then combines with molecular oxygen (O_2) to form tropospheric ozone (Zhang and Kim Oanh, 2002; Kulkarni et al., 2011). The general reaction can be written as follows:



The photochemical reactions that take place in Los Angeles-type smog give rise not only to tropospheric ozone but also to compounds like peroxyacetyl nitrate (PAN), aldehydes, other nitrates, and sulfates (Jenkin and Clemitshaw, 2000).

In April 2010 one of the most significant emissions of air pollutants from a natural source took place. The eruption of the volcano Eyjafjallajökull in Iceland led to the emission into the atmosphere of vast quantities of dust, trace elements, and other compounds that could adversely affect the environment. Moreover, the weather conditions at the time conspired to transport these pollutants very long distances away from their source. As a result, air traffic in Europe was practically brought to a standstill, and companies providing transport services sustained serious economic and material losses (Colette et al., 2010).

The movement of the dust emitted during the eruption of Eyjafjallajökull is a typical example of the very-long-distance transport of pollutants (long-range emission) (Colette et al., 2010). The movement of air pollutants from their source (volcanic eruptions, motor vehicle transport, etc.) to their deposition sites is shown diagrammatically in Figure 1.

The events described above demonstrate the potential dangers of air pollution to human beings and the environment.

MONITORING AIR POLLUTANTS

The monitoring and analysis of environmental pollutants is a rapidly developing branch of analytical chemistry (Namieśnik, 2001). A monitoring network focused on air contaminants provides an objective and reliable set of data on the state of the air over a given area at a given instant. In addition, appropriate systems for disseminating and storing measurement data enable the public to be informed about the quality of the air and to undertake suitable palliative measures within a very short time, should pollutant levels become excessive (Namieśnik, 2001; Lozano et al., 2009).

Large cities faced with the problem of air quality have invested considerable sums of money in monitoring networks.

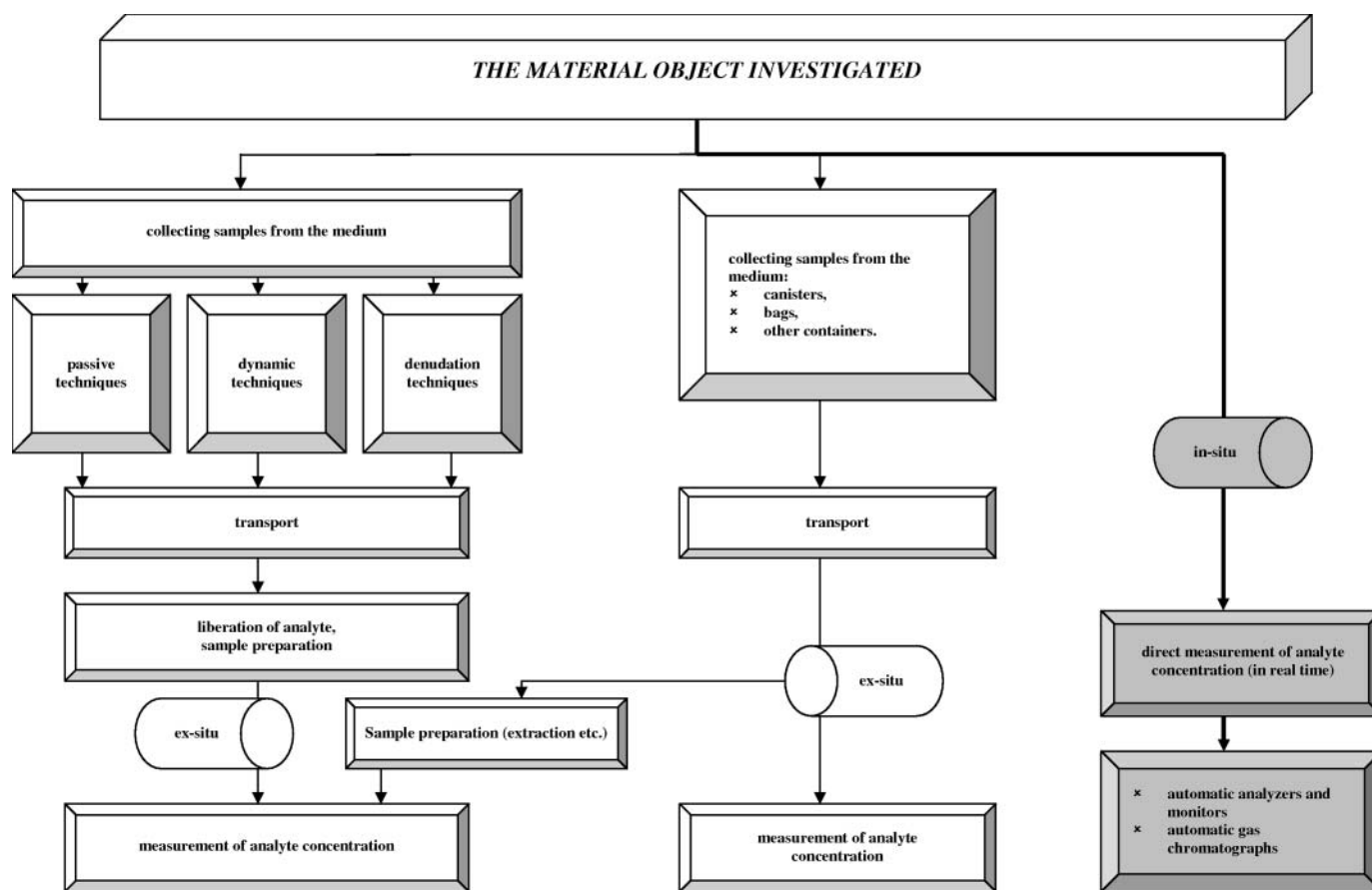


FIG. 2. Sampling techniques and monitoring equipment used to monitor contaminants in atmospheric air (Król et al., 2010).

Instruments for collecting data on air pollution should be able to cover an area of several square kilometers. The information supplied by stationary air pollution monitoring equipment can be used to derive relationships among the population of a large city, the presence of pollution, and the number of persons hospitalized (Lau et al., 2009).

In order to obtain reliable information on air quality, the right monitoring instruments are indispensable. One possible solution is a weather station which, besides collecting information on temperature, pressure, humidity, and wind speed, could also measure pollutant levels in the air. The estimated cost of such a weather station equipped with the appropriate specialist instrumentation is € 100,000 (Becker et al., 2000).

Monitoring aimed at identifying air pollutants and determining their levels is a long-drawn out, laborious, and costly process. This is because air is not a homogeneous mixture: it contains gases, liquids (aerosols), and solid bodies (various kinds of dust). Furthermore, air pollutants can diffuse, migrate, and undergo chemical reactions to produce new, dangerous compounds. Samples of atmospheric air are thus regarded as some of the most complex matrices among environmental samples (Camel and Caude, 1995; Michulec et al., 2005).

Conventional analytical procedures employed in the qualitative and quantitative determination of air pollutants involve the collection of samples and their transport to stationary laboratories (see Figure 2) (Badjagbo et al., 2007).

Because air pollutants are present at low or very low concentrations, the analytical procedure requires additional separation and preconcentration steps (Camel and Caude, 1995; Namieśnik and Wardencki, 2002; Partyka et al., 2007). Figure 3 shows, in diagrammatic form, a classification of sampling techniques with simultaneous analyte enrichment. It also supplies information on phenomena utilized for sampling and preconcentrating air pollutants (Kłoskowski et al., 2002, 2007).

The final stage in the analytical procedure to determine air quality (performed in a stationary laboratory) is to identify and determine the levels of pollutants in samples of atmospheric air. To determine organic pollutants present in air (e.g., VOCs) the usual technique is gas chromatography (GC) coupled to a suitable detector, like a flame ionization detector (FID), photoionization detector (PID), or mass spectrometer (MS). Inorganic compounds are determined by means of (Desauziers, 2004):

- Non-dispersive IR spectrometry: CO, CO₂
- Chemiluminescence: NO_x, O₃

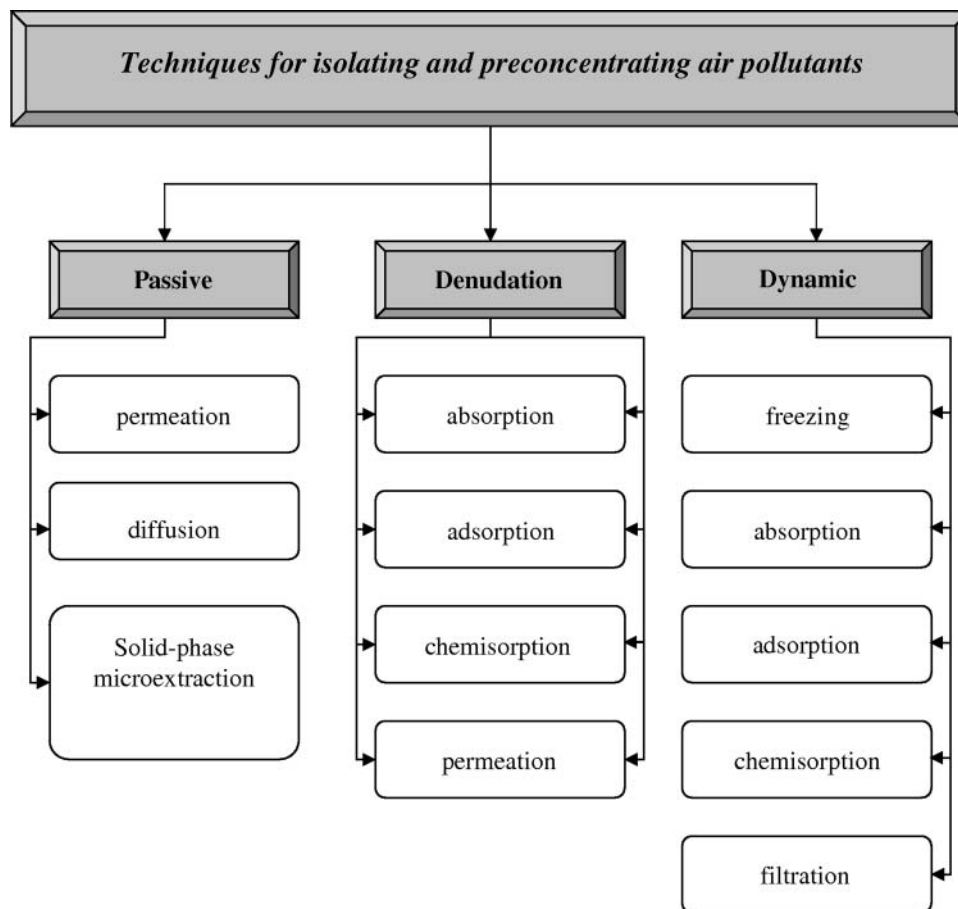


FIG. 3. Classification of techniques for sampling with concomitant analyte preconcentration and of sample preconcentration methods.

- UV fluorescence: SO_2

Because of the complexity of the analytical procedure, the time it consumes, and the costs incurred by the determination of air pollutants, attention began to turn to in situ analyses, which can be carried out without the need to transport samples. These kinds of instruments, which are becoming routine, can be classified into the following groups (Namieśnik, 2001; Namieśnik and Wardencki, 2002; Wardencki et al., 2008):

- Analyzers: instruments that are portable, handheld, or transportable, or which are part of the equipment of mobile laboratories. They can be fully automatic or semiautomatic.
- Monitors: automated instruments for continuous measuring. They are usually equipped with acoustic devices to warn of permitted pollutant levels being exceeded.

Table 1 sets out the requirements that air pollution monitors must satisfy.

MOBILE EQUIPMENT FOR AIR POLLUTION MONITORING

Mobile equipment devices for air pollution monitoring are routine in analytical practice (Król et al., 2010); they are easy and convenient to use. Their most important features include (Kolb et al., 2004; Meyer et al., 2008):

- Rapid reaction time: approximately 1 s
- Analysis performed in real time
- Mobility
- Small size
- Light weight: from 5 to 20 kg
- Simple to operate
- Low power demand

Mobile analytical equipment includes:

- Mobile laboratories equipped with appropriate instrumentation for performing analyses
- Suitcase-sized portable GCs

TABLE 1

Methodological and technical requirements for monitoring instruments (Namiński, 2001; Namiński and Wardencki, 2002; Wardencki et al., 2008)

Methodological requirements	Technical requirements
High measurement sensitivity	Automatic calibration
Analytical information supplied in continuous mode, in real time or with minimal delay	Automatic zeroing
Short response time	Safeguards against sudden power outages
Long operating time before recharging	The instrument must be equipped with: <ul style="list-style-type: none"> • An independent power source • A calibration module • A system replenishing and supplying reagents A means of automatic regeneration of replacement of spent filters for capturing solid particles

- Handheld instruments for monitoring specific pollutants such as formaldehyde, toluene, chemical warfare agents (CWAs), mercury
- Mobile robots equipped with electronic noses

Mobile Laboratories

Mobile laboratories are modified vehicles (automobiles, trucks, trains, trailers, ships/boats, balloons, aircraft) equipped with specialist apparatus for making rapid analyses of pollution (Jiang et al., 2005). Since the chemical analysis is carried out in real time and at the site of pollutant emission, the threat can be assessed very quickly and appropriate remedial action taken (Hudak et al., 1995; Chen et al., 2002). In addition, such monitoring instruments are fitted with a GPS and Internet connections, so that information can be continuously transmitted to a base. Mobile laboratories also have their own systems for powering the analytical instruments, for example, lead-acid accumulators, generators, or solar panels inserted in the vehicle roof (Ouedraogo et al., 2008; Wang et al., 2009).

Table 2 lists the equipment of some vehicles used as mobile laboratories. Analysis of the literature reports mentioned in this table shows that a basic element of practically every mobile air pollution laboratory is a permanently mounted GC with detector.

Such equipment may also include portable apparatus that can be used in the field, e.g., lightweight GCs or handheld analyzers.

Nonetheless, the greatest value of a mobile laboratory lies in its highly qualified and experienced staff. It is on their abilities that the accuracy of the air content analysis depends. A specialist team operating a mobile laboratory should consist of:

- A chemist well versed in the problems of air pollution and the construction and operation of the analytical instrumentation in the mobile laboratory
- A laboratory technician
- A driver

The number of people involved in the operation of a mobile laboratory depends largely on its size and the extent of the area where the air content analysis is to take place.

Portable Gas Chromatographs for Analyzing Air Pollution

Portable analytical equipment for field measurements is one of the most rapidly developing areas of analytical instrumentation (Makas and Troshkov, 2004). This type of equipment, fitted with highly sensitive and selective detectors with a short response time, is becoming an indispensable element of civilian and military laboratories engaged in rapid reaction to environmental contamination occurring in a particular area (Contreras et al., 2008).

Gas chromatography is the standard technique for the quantitative determination of atmospheric air pollutants (Zampolli et al., 2009). The trend toward the miniaturization of analytical equipment has led to the production of portable gas chromatographs the size of a suitcase. With LCD display units and smaller carrier gas cylinders, such equipment has become easy to transport to any particular site. Table 3 describes portable gas chromatographs used for the quantitative determination of air pollutants.

Perusal of the literature shows that most portable GC equipment is used to determine levels of CWAs. The use of portable analytical instruments for this purpose is perfectly justified, since even low CWAs levels are fatal to humans. Table 4 lists information on CWAs.

Nowadays, even though there is a total ban on the use of CWAs, there is a real threat of their being used in terrorist attacks on civilian populations (Seto et al., 2005). It is in response to this threat that air pollution monitoring increasingly focuses on this particular group of chemicals.

Handheld Equipment for Detecting and Determining Specific Harmful Substances

The construction of air quality monitoring equipment that is appropriately sensitive, is of small size, requires little power, and is cheap to operate is a challenge to modern engineers (So et al., 2009). For determining air pollutant levels one normally uses GC in tandem with a suitable detector (TDS, FID, PID, MS). But such equipment is still too large. Moreover, in order to detect and determine low and very low levels of air pollutants,

TABLE 2
Specifications of selected types of mobile laboratories

Name of mobile laboratory	Equipment	Compounds determined	References
TAGA IIe	Mass spectrometer: LPCI-MS/MS	benzene, toluene, xylenes (BTEX)	Chen et al., 2002
Mobile Analytical Laboratory manufactured by E-N-G Mobile Systems, Inc., 2245 Via de Mercados, Concord, CA 94520	Gas chromatograph hyphenated with an atomic emission detector (GC-AED)	PAHs, mainly naphthalene chemical warfare agents (CWAs)	Hudak et al., 1995
IVECO Turin V, the Mobile Laboratory of Beijing University	Ionicon/proton transfer reaction mass spectrometry (PTR-MS), ECOTECH 9830A/CO analyzer (NDIR gas filter correlation) ECOTECH 9820A/CO ₂ analyzer (NDIR gas filter correlation) ECOTECH 9810A/Ozone analyzer (UV absorption) ECOTECH 9850A /SO ₂ analyzer (fluorescence) ECOTECH 9841A/NO _x analyzer (chemiluminescence) Thermo Model 5012/Multi Angle Absorption Photometer (MAAP)	BTEX compounds carbon monoxide carbon dioxide ozone sulfur dioxide nitrogen oxides black carbon	Wang et al., 2009
A mobile laboratory designed and built by Aerodyne Research, Inc. as instrumented for the MCMA-2003	Proton transfer reaction mass spectrometer (PTR-MS) Photoionization aerosol sensor (EcoChem PAS 2000CE) Aethalometer (Magee Scientific AE-16) Aerodyne tunable infrared laser differential absorption spectrometer (TILDAS) Non-dispersive infrared (NDIR) unit (Li-Cor LI 6262) Chemiluminescent analyzer (Thermo 42C) Aerosol photometer (TSI DustTrak 8520).	volatile organic compounds (VOCs) particle-bound PAHs black carbon nitrogen dioxide formaldehyde carbon dioxide carbon monoxide nitrogen oxides (NO _x) particulate matter (PM)	Kolb et al., 2004; Jiang et al., 2005; Zavala et al., 2009
Mobile Emissions Laboratory	Non-dispersive infrared (NDIR) Non-dispersive infrared (NDIR) Chemiluminescent analyzer Flame ionization detector (FID) Heated flame ionization detector (FID)	carbon dioxide carbon monoxide nitrogen oxides methane THCs	Cocker et al., 2004
Maxxam's Mobile Laboratory	Gas chromatograph equipped with 3 detectors (TCD, FID, SCD) Gas chromatographs	volatile organic compounds sulfur dioxide mercaptans particulate matter	Maxxam Analytics Inc.
University of Minnesota Mobile Emission Laboratory	Engine Exhaust Particle Sizer TM (EEPS TM) Spectrometer Electrical aerosol detector	aerosols	Emissions Monitoring, 2009

(Continued on next page)

TABLE 2
Specifications of selected types of mobile laboratories (*Continued*)

Name of mobile laboratory	Equipment	Compounds determined	References
PSI atmospheric pollutant laboratory (IVECO)	Photoemission aerosol sensor	aerosols	Polo et al., 2001
	Scanning Mobility Particle Sizer TM (SMPS TM) Spectrometer	particulate matter	
	Gas analyzers	carbon monoxide carbon dioxide nitrogen oxides	
	Condensation particle counters (CPCs)	—	
	Aethalometer TM suspended carbonaceous particulate detector	particulate matter (PM)	
	AEROLASER AL2002	peroxide (H ₂ O ₂ , total)	
	AEROLASER AL5001	carbon monoxide	
Mine Safety and Health Administration Mobile Gas Laboratory	LI-COR (LI-6262)	carbon dioxide	Valoski, 2008
	Developed by PSI/IFU	formaldehyde	
Agilent Mobile Laboratory	NO _x TO _y (developed by PSI/Jülich/MetAir)	nitrogen oxides	Agilent Mobile Laboratory, 2003
		PAN	
Virginia Tech Mobile Chemistry Laboratory (Volvo)		nitric acid (V)	Harris, 1999
		volatile organic compounds	
	2 gas chromatographs		
	Gas chromatograph with FPD or MSD	chemical warfare agents (CWAs)	
	Fourier-transform infrared spectrometer	volatile organic compounds (VOCs)	
	4 gas chromatographs		
	UV-vis spectrometers		

an extra, analyte preconcentration step has to be included in the analytical procedure (Huang et al., 2010). This implies a higher cost and a longer time of analysis.

The increasing interest in equipment for analyzing air pollutants has led to the development of devices for determining particularly harmful air pollutants. Such instruments must obviously be highly sensitive to the target compound, be small in size, be easy to operate, and supply analytical information within a very short time (Huang et al., 2010), without the necessity for a sample preparation step. These devices are self-powered and can be connected to a computer (Wardencki et al., 2008). Table 5 sets out parameters characterizing handheld devices for determining specific air pollutants.

New Approaches in Mobile Monitoring of Atmospheric Air

At present, most air pollution monitoring systems consist of static sensors deployed at selected sites in an area (Trincavelli et al., 2008). But in the near future, it will become possible to monitor air quality using mobile robots fitted with an artificial sense of smell known as an electronic nose (e-nose). Such equipment is expected to:

- Identify many different odors
- Be very sensitive to pollutants
- Have a rapid response time

Electronic noses are constructed from a range of gas sensors, each with a different sensitivity, for example (Ragazzo-Sanchez et al., 2008):

- Metal oxide semiconductor sensors
- Surface acoustic wave (SAW) sensors
- Quartz resonators

Mobile robots equipped with electronic noses can be used for a variety of tasks, such as (Romain et al., 2005; Lilienthal et al., 2006):

- Localizing the source of a specific, unpleasant odor
- Producing maps of odor concentrations in a given area
- Continuous monitoring in a given area

This type of mobile equipment has demonstrated its utility in the detection of lethal colorless and odorless gases like carbon monoxide. The combination of a mobile robot with an appropriate sensor enables the composition of air to be analyzed in any place where humans beings are (Lilienthal et al., 2006).

TABLE 3
Specifications of portable gas chromatographs used for monitoring air pollution

Name of portable gas chromatograph	Detector	Application in air pollution monitoring	Comments	References
HAPSITE smart gas chromatography-mass spectrometry (GC/MS) system	Mass spectrometer (MS)	Determination of chemical warfare agents (CWA): tabun, sarin, soman, and mustard gas Determination of volatile organic compounds (VOCs)	Dimensions: 46 × 43 × 18 cm, Weight: 16 kg Analyte concentration level: ppbv Carrier gas: nitrogen (N ₂)	Smith et al., 2004; Sekiguchi et al., 2006; Fair et al., 2009, 2010
Viking 572 GC-MS	Mass spectrometer (MS)	Determination of chemical warfare agents (CWAs): tabun, sarin, soman, and mustard gas	Based on SPME Dimensions: 61 × 31 × 45 cm Weight: 30 kg - without pump Carrier gas: hydrogen(H ₂)	Smith et al., 2004
Field GC-MS, consisting of the original "concentrator-thermodesorber" (CTD) unit	Mass spectrometer (MS)	Toxic substances	Weight: 90 kg Power consumption: 250 W Analyte concentration level: ppt Carrier gas: helium (He)	Makas and Troshkov, 2004
Field-portable, high-speed GC/TOF-MS	Time-of-flight mass spectrometer (TOF-MS)	Determination of chemical warfare agents (CWAs)	Analyte concentration level: ppb	Syage et al., 2001
Hand-portable gas chromatograph-toroidal ion trap mass spectrometer (GC-TMS)	Ion trap mass spectrometer (TMS)	Determination of chemical warfare agents (CWAs) Determination of toxic industrial chemicals (TICs)	Dimensions: 47 × 36 × 18 cm Weight: < 13 kg Based on SPME	Contreras et al., 2008
Micro-FID (GC-μFID)	Flame ionization detector (FID)	Determination of atmospheric hydrocarbons (propane, benzene, toluene, and p-xylene)	Analyte concentration level: ppm	Kim and Pal, 2008
Portable gas chromatograph with tunable retention and sensor array detection	Detector comprising an array of polymer-coated surface acoustic wave (SAW) microsensors	Determination of chemical warfare agents (CWAs)	Dimensions: 32 × 32 × 10 cm Carrier gas: scrubbed ambient air Analyte concentration level: ppb	Lu et al., 2003
Portable gas chromatograph with integrated micromachined injector and thermal mass detector (TCD)	Thermal conductivity detector (TCD)	CH ₄ , CO	Dimensions: 15 × 45 × 30 cm Weight: 3.5 kg Analyte concentration level: ppm Carrier gas: helium (He)	Dziuban et al., 2004, 2005

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TABLE 3
Specifications of portable gas chromatographs used for monitoring air pollution (*Continued*)

Name of portable gas chromatograph	Detector	Application in air pollution monitoring	Comments	References
Bruker-Daltronics GC/MS system	Mass spectrometer (MS)	Determination of chemical warfare agents (CWAs) Determination of volatile organic compounds (VOCs)	Weight: 62 kg	Ho et al., 2001
Femtoscan hand portable gas chromatograph/ion mobility spectrometer (GC/IMS) instrument	Ion mobility spectrometer (IMS)	Determination of volatile and semi-volatile air components	Very small Very light Analyte concentration level: ppb No carrier gas	Ho et al., 2001
3000 Micro GC gas analyzer detector (TCD)	Thermal conductivity	Compatible with mixtures in the gaseous phase; typically for compounds with boiling points < 250°C	Weight: 16.6 kg Dimensions: 41.3 × 36.4 × 15.5 cm Carrier gas: depending on requirements helium (He), argon (Ar), nitrogen (N ₂) Analyte concentration level: ppm	INFICON

One such mobile robot is Rasmus (Trincavelli et al., 2008), which is equipped with an anemometer for measuring wind speed and an electronic nose. This prototype is to be used for monitoring atmospheric air. The electronic nose contains six sensors for identifying the following contaminants (Trincavelli et al., 2008):

- Hydrogen, carbon monoxide: 2 sensors
- Ammonia, hydrogen sulfide, VOCs: 1 sensor
- Methane: 1 sensor
- Organic solvents: 1 sensor
- Carbon dioxide: 1 sensor

With so many sensors such an electronic nose can provide information on the levels of many gases potentially present in the air. This prototypical robot is also fitted with sensors for recording temperature, humidity, and wind speed (Trincavelli et al., 2008).

The construction of mobile robots for monitoring air pollution is an engineering challenge; with properly configured sensors and software, such devices can bring about a substantial improvement in the quality of air pollution monitoring.

DEVELOPMENTS AND FUTURE TRENDS IN MOBILE AIR POLLUTION MONITORING DEVICES

Gas chromatography is still the best technique for analyzing complex mixtures of gases, such as are present in air. But the standard GCs are cumbersome, expensive, and consume too much energy; moreover, the time of analysis is long and the detectors are not sufficiently sensitive to air contaminants present at low and very low levels. They are therefore not commonly used in the field (Lu et al., 2005; Ali et al., 2009; Halliday et al., 2010).

One of the major trends in the field of gas detection involves the miniaturization of analytical techniques such as gas

TABLE 4
Degree of toxicity of chemical warfare agents (OWR AG)

Name of compound	Mustard gas	Sarin	Soman	Tabun	Lewisite
Lethal dose (LD ₅₀) ^a (mg/kg) (percutaneous)	60	24	5–15	14–21	15–20
Lethal concentration (LCt ₅₀) ^b (mg·min/m ³)	inhaled: 1 500	100–200	40–70	300	inhaled: 1 200

^a LD₅₀: the dose that kills 50% of the exposed population.

^b LCt₅₀: the concentration time that will kill 50% of the population. Ct is a measure of exposure to a vapor or aerosol

TABLE 5
Specifications of handheld instruments for determining specific air pollutants

Instrument	Pollutants determined	Specifications	Concentration level	References
Palm portable mass spectrometer (PPMS)	CWAs, benzene, toluene, xylenes,	Weight: 1.48 kg Dimensions: $8.2 \times 7.7 \times 24.5$ cm Battery 3000 mAh, operating time ca. 10 h Response time: less than 1 s Device fitted with USB port, enabling configuration of such instrument functions as individual hardware control, vacuum system control, self-diagnosis, mass spectrum measurement, result display, identification from data library, alarm, background noise subtraction, spectrum average, parameter setting, data processing, data library register	ppm	Yang et al., 2008
Photometric gas sensor for toluene	Toluene	The device consists of: Pump (flow rate: 480 mL/min) Glass filter of diameter 21.5 mm Reagent: I_2O_5 Circular chip slot White LED (430 ~ 750 nm) Photodiode: 460 nm Display screen Four AA batteries and stabilization circuit to power the photodiode and white LED	ppm	Kawamura et al., 2006
Photometric gas sensor for formaldehyde	Formaldehyde	The device consists of: Pump (flow rate: 480 mL/min) Glass filter of diameter 21.5 mm Reagent: 4-amino hydrazine-5-mercapto-1,2,4-triazole (AHMT) and KOH Circular chip slot White LED (430 ~ 750 nm) Photodiode: 540 nm Display screen Stabilization circuit to power the photodiode and white LED Degree of color change is recorded by measuring the reflected light at 540 nm with photodiode and LED Four AA batteries	ppm	Kawamura et al., 2005
APCI/Mini 10.5	Benzene, toluene, ethylbenzene	The device consists of: Discontinuous atmospheric pressure interface (DAPI) Mini 10.5 handheld mass spectrometer APCI ion source fashioned from the easily machined thermoplastic polyetherether ketone (PEEK) Dimensions: Mini 10.5: $34 \times 22 \times 19$ cm Weight Mini 10.5: 10 kg Maximum airflow rate: 2.5 L/min Optimal discharge voltage for the corona APCI: 5 kV	ppb	Huang et al., 2010

(Continued on next page)

TABLE 5
Specifications of handheld instruments for determining specific air pollutants (*Continued*)

Instrument	Pollutants determined	Specifications	Concentration level	References
Minianalyzer for atmospheric mercury determination	Mercury	Dimensions: 45 × 42 × 20 cm Weight: 13 kg The device consists of: Low pressure mercury lamp Flow cell Radiation detector (photomultiplier tube, sensitive only to radiation of $\lambda < 200$ nm) Electronic amplifying and displaying system Determination by cold vapor atomic absorption spectrometry (CVAAS) at 184.9 nm mercury line	$\mu\text{g}/\text{m}^3$	Danet et al., 2009
Prototype handheld device provides real-time radiation and ozone monitoring.	Ozone	Thermally co-evaporated films of mixed oxides, such as indium (In_2O_3), zinc (ZnO), and tin (SnO_2), Zone interacts with the outermost layers of the sensor, producing a change in its electrical properties, such as conductance	ppb	Korostynska et al., 2008

chromatography. Miniature GCs, also known as micro GCs (μGCs), are constructed from many microcomponents (Narayanan et al., 2010). They are used as microelectromechanical systems (MEMS) in the collection and measurement of gases (Lindner, 2001; Ohira and Toda, 2008); as a result, miniaturized gas chromatographs have a lot of advantages (Lu et al., 2005; Ohira and Toda, 2008; Zampolli et al., 2009; Chang et al., 2010):

- Rapid time of analysis thanks to the use of a microfluid channel
- With their high surface-to-volume ratio a high pre-concentration factor can be achieved; resolution and sensitivity (ppb level) are thus both high
- The elements of the μGC heat up and cool down very quickly, which considerably shortens the time of analysis
- Low energy consumption, especially by the heating device
- Very small amounts of solvents are required, so μGCs are regarded as environmentally friendly
- The entire analytical equipment is small in size and can therefore be readily transported to any site

The μGCs used for determining air pollutant concentrations may be built from such microcomponents as:

- Preconcentrator/focuser: the use of analyte preconcentration devices substantially increases detector sensitivity. These consist of adsorbent materials placed on the heating device. The microcomponents for precon-

centrating analytes may vary in size from a few to 15–20 mm (Gracia et al., 2008; Camara et al., 2010),

- Separation column: ensures very rapid separation of a mixture of analytes. The microcolumns occupy an area of a few cm^2 and are no more than 10 m long. Silicone is the usual packing material in chromatographic microcolumns. The microcolumns themselves can be made from porous silicone, carbon nanotubes, parylene, metals, or ceramics. Microcolumns may have different configurations (Halliday et al., 2010; Radadia et al., 2010):
 - Spiral
 - Circular-spiral
 - Square-spiral
- Detector: the usual detectors in μGC devices are:
 - Micro thermal conductivity detector (TDC) (μTDC) (Cruz et al., 2007; Narayanan et al., 2010),
 - Metal oxide (MOX) (Zampolli et al., 2009),
 - SAW array (Lindner, 2001),
 - Micro MS (Hauschild et al., 2007)
- average carrier gas velocity in the range of 5–65 cm/s (Radadia et al., 2010)

Micro GCs are an excellent example of a modern combination of electronics and mechanics. As a result, air pollutants can be analyzed faster, more efficiently, and more cheaply. Developments in the miniaturization of laboratory equipment are moving towards the construction of an air pollution monitoring device known as a lab-on-a-chip (LOC).

LOCs combine laboratory functions on a single chip from a few square mm to a few square cm in area. They are usually made from glass or silicone, but these materials are increasingly being replaced by polymers like polydimethylsiloxane (PDMS) (Hongbin et al., 2009).

The most important element of any *Lab-on-a-Chip* is the microchannel. This where the sample may be successively pre-concentrated, separated or mixed before passing on to the final determination of its constituents (Yu et al., 2009).

Labs-on-a-chip have mostly been applied in such fields as medical diagnostics, biochemical assays, proteomics, genomics, and, one of the most promising applications, clinical diagnostics (Grabowska et al., 2007).

It is to be expected that work will soon start on the production of a lab-on-a-chip for analyzing air pollutants. The examples of μ GCs means we can look to the future with confidence.

ABBREVIATIONS

AED	atomic emission detector
AHMT	4-amino hydrazine-5-mercapto-1,2,4-triazole
APCI	atmospheric pressure chemical ionization
BTXE	benzene, toluene, o-, m-, and p-xylene, ethylbenzene
CPCs	condensation particle counters
CTD	concentrator-thermodesorber
CVAAS	cold vapor atomic absorption spectrometry
CWA	chemical warfare agent
DAPI	discontinuous atmospheric pressure interface
FID	flame ionization detector
FPD	flame photometric detector
GC	gas chromatography
GPS	global positioning system
IMS	ion mobility spectrometer
LCD	liquid crystal display
LED	light-emitting diode
LOC	lab-on-a-chip
LPCI-MS/MS	low pressure chemical ionization/tandem mass spectrometry
MAAP	multi-angle absorption photometer
MEMS	microelectromechanical system
MOX	metal oxide
MS	mass spectrometry
MSD	mass selective detector
NDIR	non-dispersive infrared
PAH	polycyclic aromatic hydrocarbon
PAN	peroxy acetyl nitrate
PDMS	polydimethylsiloxane
PEEK	polyetherether ketone
PID	photoionization detector
PM	particulate matter
PPMS	palm portable mass spectrometer
PTR	proton transfer reaction
SAW	surface acoustic wave
SCD	sulfur chemiluminescence detector

SPME	solid-phase microextraction
TAGA	trace atmospheric gas analyzer
TCD	thermal conductivity detector
THCs	total hydrocarbons
TIC	toxic industrial chemical
TILDAS	tunable infrared laser differentia absorption spectrometer
TMS	trap mass spectrometer
TOF-MS	time-of-flight mass spectrometer
USB	universal serial bus
VOC	volatile organic compound

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