

Air contamination exposure measurements of organic solvents — Past and present

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GUILLEMIN MP. Air contamination exposure measurements of organic solvents — Past and present. *Scand J Work Environ Health* 11 (1985): suppl 1, 33–43. The increase in industrial development and advanced manufacturing processes has led to a comparative increase in the use of solvents for cleaning and maintenance and in their use as constituents of certain manufactured products and for various other purposes. The strategy and methodology for the sampling and analysis of solvents have developed drastically during the last two decades. The introduction of solid sorbents has allowed the use of tubes and badges, which have promoted personal sampling. The performance of pumps (for active sampling) has increased, and the weight of pumps has decreased. Passive sampling is still under study to establish its advantages and limitations but has already shown to be very useful in many situations. Stationary sampling finds its application in control effectiveness assessments or in circumstances where personal sampling is not feasible. Gas chromatography is certainly one of the most frequently used methods for analyzing solvents. There are however many other analytical methods available, but they have to be selected according to the species considered and to many other factors, such as the purpose of the measurements, the available instrumentation, the field characteristics, etc. The rapid growth of microcomputers and the improvement in miniaturization have favored the development of direct-reading instruments of all kinds. These instruments may be very helpful to the industrial hygienist since they give a quick response, but their apparent simplicity may lead to their misuse.

Key terms: development, exposure assessment, general, history, methodology, solvents, strategy, trends.

Introduction

“Measurement has given the industrial hygienist a veritable crystal ball which enables him to predict with a high degree of accuracy the future effect on worker health of a work environment occupied today.” This enthusiastic and highly optimistic declaration by W Fredricks appeared in 1956 in the preface of the first encyclopedia on industrial hygiene instrumentation (68); it illustrates how important a quantitative approach was considered in the early days of exposure measurements. After almost 30 years of development and progress no one would share this optimism!

The purpose of this paper is to introduce, for those not specialized in this area, the concept of workers' exposure assessment, which cannot be limited to sampling and analytical methods. In order to get a general and critical overview of the subject, a few relevant aspects will be discussed in the perspective of the evolution of this multidisciplinary field. I have also restricted the subject to the vapor phase of solvents, and not the liquid phase (aerosol, mist), since the vapor phase represents by far the most important one.

A solvent is, by definition, any liquid which will dissolve another substance. The organic solvents are

usually classified into various family groups having similar solvent and chemical characteristics (table 1). A more precise classification does not appear justified in this context. A difficulty in estimating the nature of solvents comes sometimes from trivial or conventional names such as “Stoddard solvent” (or white spirit), ligroin, turpentine, cellosolve, naphtha, kerosene, or benzene. In addition to classification by chemical nature, solvents are characterized by different properties, the most significant ones for occupational hygiene being vapor pressure (volatility), solubility (in water, blood, fat, etc), flammability, density, and so on.

Development of the industrial use of solvents

At the turn of the century there were roughly a dozen organic solvents in widespread use. Today there are

Table 1. Solvent production by category^a (60).

Category	Total 1979 (%)	Expected demand 1988 (%)
Aliphatic hydrocarbons	28	30
Aromatic hydrocarbons	20	12
Halogenated hydrocarbons	18	17
Alcohols	14	17
Ketones	10	11
Esters	7	8
Others	3	5

^a Total production in 1978: 4.3 million tons = 1.5 billion US dollars.

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hundreds of specific substances and thousands of different mixtures used in various industries of all sizes. The introduction of cracking and hydrogenation processes around 1920 constituted the real start of the development of organic solvents. This technological evolution stimulated the parallel growth of solvent species and use, especially in the surface coatings industry. The introduction of chlorinated hydrocarbons, nonflammable and with a strong affinity for oils and fats, was considered a major step in this development. At the same time gluing processes with new adhesives containing solvents replaced the mechanical assembly of pieces in shoe, leather, and hat factories (34).

After 1930 solvent recovery was started in some industries, but in others it was regarded as an unnecessary complication despite its profitability. In 1978, 18 % of the total demand for solvents in the European Economic Communities (EEC) came from recovery, and 36 % is expected for 1988, but 50 % could be in fact recovered (20).

The discovery of resins, synthetic fibers, and other plastics gave a new impetus to the development of solvents between 1930–1960, although cellulose and some formaldehyde derivatives were already being manufactured.

Table 2 shows the main industrial use of solvents in the EEC. Actually, the multipurpose or universal solvents tend to be replaced by specific substances more appropriate to the process or to the manufacture concerned.

The global trend in production for the 1980s has been estimated to be an increase of 1.7 % per year. It is expected in the household, rubber, pharmaceutical, and fine chemical sectors, whereas a decrease is expected in the surface coating industry due to legislation aiming to control emissions.

Need for occupational exposure assessment

The ultimate goal of any evaluation of worker exposure is to protect the workers' health and well-being. This goal assumes that the health and well-being significance of any exposure level is known — in other words that the dose-response or dose-effect relationship has clearly been established. Unfortunately, for only a rather limited number of solvents, has this relationship been sufficiently well characterized. For others conclusions have to be drawn

from much weaker bases (44). Such estimations constitute the scientific background of the permissible levels (occupational standards) used almost everywhere.

The permissible exposure levels (threshold limit values), representing the most important tool to protect workers, have indeed bases that are too weak, as confirmed by the periodic revisions which most of the time lower the values. Ulfvarson (63) has discussed the problem of the indirect approach of exposure assessment in epidemiologic research and its related biases. Probably the best indirect evaluation is obtained by the exact reconstitution of past work conditions (15). To consolidate these bases, epidemiologic studies — only the ones giving real field results — supported by reliable exposure results, must be promoted. Therefore many more studies should be oriented towards exposure assessment and the parallel surveillance of workers' health and well-being.

Quantification of occupational exposure in the past

The first quantitative approach to occupational exposure can be traced back to 1886 when K Lehmann established the first maximum allowable concentrations in Germany for some organic solvents and some gases. He introduced systematic chemical analysis into some work areas and compared the prevalent concentrations with the workers' health status. In addition he performed controlled short-term exposure experiments with volunteers and laboratory animals (29).

The development of the permissible exposure levels started in the 1940s with publication in the United States of the first list of maximum allowable concentrations (MAC), later renamed threshold limit values (TLV). The need of reference values to protect workers grew much more rapidly than the availability of manpower, instrumentation, and methods to fill the gaps in existing knowledge. This situation is in fact still true today.

Sampling and analytical methods have developed exponentially since the publication of these first hygienic standards. In this short summary of the methodology used in the past, I have covered the period between the 1950s and the late 1960s. No systematic historical study has been made during the preparation of this overview, which is based on a compilation of "old" documents and on personal experience. This statement implies that some subjectivity will be difficult to avoid.

Sampling strategy and sampling methods

During the time in question, sampling strategy did not exist as such, but some of the elements constituting the actual trend in strategy concept were already being discussed. The available instrumenta-

Table 2. Main industrial use of organic solvents in the European Economic Communities in 1980 (34).

Use	Percentage of total use
Surface coatings	43
Cleaning and degreasing	14
Household products	8
Adhesives	7
Pharmaceuticals	6
Others (including oil extraction)	22

tion and method sensitivity did not allow much flexibility, and personal sampling was not possible, although the importance of sampling air in what is now called the "breathing zone" was recognized. The idea to adapt the sampling time to the pharmacokinetic behavior of the considered solvent was already borne in 1966 (47), but it did not find any echo.

Elkins (13) recommended taking three sets of samples (one representing the operator exposure, one of the general air, and one near the probable source of contamination). The samplings were planned also after preliminary investigations and grab (qualitative) sampling, and after some considerations and calculations about the probable levels of contaminants in air (vaporization rate, room volume, air exchange, etc). The sampling devices were mainly bubblers or tubes containing activated charcoal or silica gel.

Figure 1 shows an example of air sampling with an impinger for trichloroethylene in the operator's zone with a hand-driven pump (23). The electric air moving devices were so heavy and cumbersome that most samplings were carried out at fixed locations.

The condensation method using dry ice (solid carbon dioxide) at -80°C was also proposed for some solvents, but it was less convenient than other methods.

All the aforementioned methods concentrated the solvent to be analyzed, and this step represented a significant advantage at a time when analytical methods were not very sensitive. This lack of sensitivity also explains why methods in which the contaminant was not concentrated in an appropriate medium, such as rigid containers, plastic bags, or syringes, could not be considered for exposure evaluation. They were however useful for grab sampling and for preliminary tests. References 68 and 32 give a good overview of the old sampling methods.

Analytical methods and direct-reading instruments

Absorption spectroscopy in the infrared, visible, and ultraviolet range can be considered as the principal method of analysis for solvents during this period.

The spectroscopic method may be divided into direct and indirect methods. The direct method consists of quantifying the amount of solvent present in the sample by measuring the absorbance (or transmittance) of the solvent itself at an appropriate wavelength. Such a method works for instance for some aromatic hydrocarbons. The indirect methods are based on the reaction of the solvent with another substance (or other substances) to form a compound with a stronger absorption than the solvent alone. Many such methods have been developed (13, 50, 57). Some are very sensitive, some are very specific, but very few combine both qualities.



Figure 1. Air sampling with an impinger in the operator's zone and a hand-activated portable pump.

Simple instrumentation such as color comparators and simple sampling devices were introduced to carry out quick measurements in the field (61). For other solvents, methods other than colorimetric reactions were in use, such as acid-base or oxydo-reduction titrations.

More elaborate methods, such as gas chromatography, were appearing in well-equipped research laboratories, but they were not yet part of occupational hygiene instrumentation.

Direct-reading instruments (68) appeared very early and, due to their simplicity and convenience for detecting and evaluating airborne solvent concentrations, rapidly found a rather large use in industry. Detector tubes or impregnated papers encountered rapid success.

Explosimeters found extensive application in the detection and measurement of flammable solvents in the range of high concentrations (lower explosive limit), first to determine explosion hazard but later to measure concentrations in a much lower range through an increase in the sensitivity of their electrical detection system.

Chlorinated hydrocarbons have the property, in addition to that of producing a green flame when burning with copper, of modifying the emission spectrum of nitrogen produced in an electric arc. This property gave rise to the manufacture of an instrument called the "Davis Halide Meter" which became extensively used, especially in the metal cleaning industry.

Other direct-reading instruments were developed during this period. In most cases these instruments were not adapted to quantitative exposure assessment (spot values, no recorder, no linear response, etc) and had a more qualitative than quantitative function.

Treatment and interpretation of results

Hygienists and analytical chemists were very much aware of the limitations of their methods but had restricted means of taking them into account. The

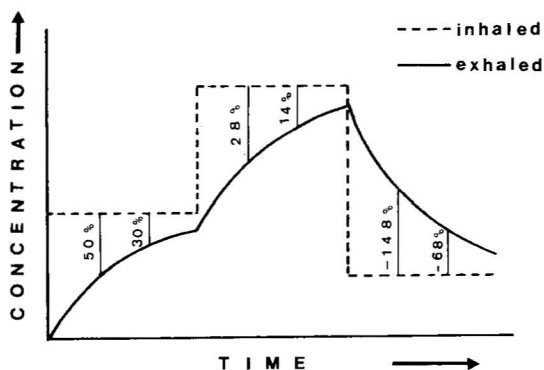


Figure 2. Hypothetical pattern of the breath concentration of a solvent with time during three consecutive exposure periods to different stable concentration levels. The indicated percentages correspond to the retention of the solvent in the body.

lack of specificity probably represented the main drawback of both the sampling and the analytical methods.

It may be supposed that under many circumstances results have been abusively used, especially in cases where a small number of measurements was considered (often not by the hygienists themselves) as representative of the true exposure of the workers.

The exposure evaluation and its health significance were usually determined separately, and therefore any comprehensive approach was prevented. It is now well known that the factors that influence exposure and those which influence the effect of exposure may be the same or may be interrelated, eg, work methods, effort, physiological characteristics, smoking, drinking or eating habits, personal hygiene, etc.

It may be concluded that the field investigations carried out to evaluate the worker exposure during this period suffered from technical limitations and from the lack of a comprehensive multidisciplinary approach.

Current exposure assessment

The introduction by White et al (64), in 1970, of solvent sampling on small charcoal tubes and gas chromatographic analysis after elution with carbon disulfide constituted a major breakthrough in methodology and the beginning of a new era in this field. The period discussed in this section includes in fact the transition, still in progress, whereby the "art of ambient monitoring to determine personal exposures is becoming a science" (2).

Sampling strategy

I would first like to consider the best strategy with which to assess worker exposure as reliably as possible, being aware that in many field situations com-

promises must be accepted for practical or economic reasons.

Worker selection. The drawing of conclusions on the relationship between exposure and effect (response) implies knowledge of the personal, individual exposure of the worker, and therefore personal sampling appears to be the preferred technique. However, when the number of workers concerned increases, it becomes rapidly unrealistic to sample everybody. Choices have to be made either at random, if the exposure is estimated to be fairly homogeneous (39), or according to the "exposure zone concept," if the exposure appears to be related to a job, process, location, or some other parameters (6).

Sampling duration. A full period of sampling, very convenient to check compliance with a standard, corresponds to the arithmetic mean of the exposure and is, in principle, proportional to the solvent intake (the amount that enters the respiratory system), but not necessarily to uptake (the amount retained in the body). Figure 2 illustrates this fact in a primitive way to avoid mathematical formulas. Very often it is assumed that some equilibrium between the inhaled and exhaled concentration is rapidly attained, ie, that the proportion of retention is roughly constant, but this is not true when changes in concentration levels occur at intervals approximately equal to or smaller than the "apparent half-time" (time to reach 50 % of the maximum) of the solvent.

In fact, up to now, much effort has been expended to determine properly compliance with a standard (39), but little effort has been given to the best way to approach the body burden or the burden of the target organ, which is more relevant to the assessment of toxic effects. Roach (47) was probably the first to stress the importance of the apparent biological half-time of a substance in the determination of the appropriate sampling time for the assessment of uptake. By using a simplified model, he showed that the sampling duration should be between 0.1 to 0.3 times the apparent half-time of the considered substance to take into account the significance of peaks for body burden. A longer period dampens the variations too significantly and gives rise to an underestimation of uptake (48). For solvents with short half-times (< 20 min), such as acetone, amylacetate, ethyl ether, and benzene, the recommended sampling time (2–6 min) implies an unrealistic number of samples to cover one shift (80–120 samples). A continuous direct-reading instrument would probably best fit the pharmacokinetic requirements in this case, provided the response time of the instrument is similar to the apparent half-time of the compound (48).

As stressed by Ulfvarson (63), some critical situations ("resonance") with highly fluctuating concentrations may occur where the duration of the peaks

is much longer than the solvent half-time, and it is not compensated for by a sufficiently long interruption between the peaks. Other authors have discussed this important kinetic aspect in relation to modifying the standard for unusual work schedules or to avoiding a possible chronic accumulation (31, 35, 51). Unfortunately these considerations have not been applied in the field and still remain academic. In fact, much more emphasis should be placed on toxicokinetic aspects (2). The simplified models do not take into account the target organs and the differences in their specific half-times nor their differences in (toxic) response to a solvent. Some target organs may be damaged depending on the intensity of exposure (peak height); others may respond to the total dose received (integration of exposure with time). A more elaborate approach is possible for some solvents with mathematical models, which have already proved their usefulness (18), but this possibility has not yet been investigated.

Occupational hygienists, toxicologists, and physicians have been concerned by the problem of peak height for a long time. It was obvious that some upper limit should be given independently of the time-weighted average since fatal concentrations may occur briefly without considerably affecting an 8-h average. The solutions proposed were not satisfactory up to 1983 when the "Deutsche Forschung Gemeinschaft" (8) introduced, in its "MAK-Werte" list, a new concept by taking into consideration both

the mode of action and the biological half-time in the determination of short-term values.

Sampling duration also concerns long-term exposure estimations since chronic effects may take a long time to occur. Then day to day, week to week, month to month, and year to year variations and possible trends must be taken into account.

Choices of contaminants to be sampled. Real field situations make the choice of relevant factors very problematic and require good professional judgment and a multidisciplinary approach. Even in cases where the exposure assessment concerns only one specific solvent, the sampling strategy cannot be reduced to this single substance since the health effect possibly observed could be attributed to other contaminants or stresses. Therefore a list of potentially relevant parameters has to be first established. Table 3 gives a few examples of such factors.

It should be recognized that this type of approach is not yet systematic and that probably some important factors are still overlooked.

Choice of the sampling and analytical methodology. Standardized methods are, in principle, those preferred. It should be stressed however that many different sources of errors not usually tested in the validation procedures occur in the field and have to be looked for by the hygienist and tested in the qua-

Table 3. Common difficulties associated with the choice of relevant factors for assessing exposure to solvents.

Difficulty	Reference
Mixtures	
Selection of the relevant substances in a mixture of many solvents	
Hidden factors	
Impurities of toxicologic significance	
Benzene in toluene	Bureau International du Travail (3)
Dioxane in 1,1,1-trichloroethane	Henschler et al (30)
Chemical transformation	
Pyrolysis (of plastics for example)	Frostling et al (21)
Photolysis (of chlorinated hydrocarbons for example)	Limasset & Margossian (36)
Interaction between factors	
Chemical reactions between contaminants	
Formation of styrene oxide with styrene and catalyst	Pfäffli et al (46)
Formation of bis(chlormethyl)ether with methyl alcohol and hydrochloric acid	Frankel et al (19)
Adsorption or absorption processes	
Dust or mist may adsorb vapors	Cautreels & Van Cauwenberghe (4)
Biological interactions	
Interferences in the metabolism due to concomitant exposure	
Hexane - toluene	Perbellini et al (45)
1,1,1-trichloroethane - xylene	Savolainen et al (52)
Interferences in the effect	
Dichloromethane and carbon monoxide	Fagan et al (16)
Cyclohexanone and vibration	Henkel & Rublack (28)
Interference from life-style	
Smoking, eating, drinking habits	Wilson et al (66)

lity control program (59). For instance the influence of the sampling line (or tubing), according to its nature and its length, may give rise to losses by adsorption, diffusion, or permeation and will be overlooked if not tested (55).

Besides the chemical and physical considerations involved in selecting the appropriate methodology and instrumentation (explosive or corrosive atmospheres, magnetic fields, etc), other aspects will have some influence, eg, physiological or psychological parameters, type of work, type of protection used, location of emission sources, control systems, turbulences, drafts, etc. Advice and help from a multidisciplinary team are again necessary.

Other aspects. Physiological, biological, and toxicologic factors have also to be considered in relation to both personal and biological monitoring. For instance, the physical work load, which increases respiration rate, increases the intake in the same proportion and may be of major importance in some situations (1, 11). The usual sampling pump has a constant flow rate and cannot take this factor into account. Droz & Nicolet (12) have devised a pump regulated by heart rate to determine the influence of work load under field conditions.

When investigations are aimed not only at assessing the worker's exposure, but also at detecting and quantifying the influence of other factors (process, work habits, season, etc), statistical requirements have to be fulfilled (39).

Sampling methods

Charcoal. The sampling method which consists of retaining solvent vapors on activated charcoal is by far the most widespread. As already mentioned, the use of small charcoal tubes connected to a small portable pump (active sampling) was introduced in 1970 (64). In 1976 it was shown that a layer of charcoal placed in a badge and exposed to a solvent vapor can collect the vapor by diffusion through air or through a plastic membrane (passive sampling) (62). Both methods, very simple and convenient to use for personal sampling, have their own advantages and disadvantages.

The pump constitutes a significant source of error and of disturbance, and active sampling requires frequent checks of the flow rate. Small pumps manufactured according to modern technology with improved performances have now appeared on the market however. A major advantage of this method over passive sampling is the flexibility gained in the choice of an appropriate sampling time. Even short periods are possible because the analytical sensitivity does not represent a major limitation, since the flow rate of the pump may be increased if needed.

Badges however do not have such flexibility, their "flow rate" being determined by the diffusion coef-

ficient through the layer in front of the charcoal (air or plastic membrane). It corresponds to very low flow rates, which render the badges inconvenient for short-term sampling. However their small size, their easy manipulation, and the absence of a pump represent important advantages and make this sampling method very attractive. Their introduction was received with some scepticism as to their performance. But after eight years of theoretical, experimental, and field studies this scepticism has changed to optimism (49).

A considerable number of publications have been issued on the subject of charcoal sampling methods, and research and development are still in progress (37, 42, 49, 59).

Other methods. I have not considered here the methods specifically restricted to grab or spot sampling but have briefly described other available methods.

- *Containers:* Whether flexible, such as plastic bags, or rigid, such as glass bottles, tubes, cans or syringes, containers belong to the category of "other methods." The volume of the device is limited for practical reasons, and the solvent vapor is not concentrated in any way, which requires the use of a sensitive analytical method. Air enters the containers by different ways (pump, critical orifice and vacuum, motor-driven plunger, etc). When used in conjunction with gas chromatography, the sample can be introduced directly without any preliminary treatment. Disadvantages concern the stability of the samples.
- *Bubblers:* Liquid sorbents may be useful for some reactive solvents difficult to sample by other means. Different types and forms of bubblers exist, the spill-proof impinger (27) and the tube closed by hydrophobic membranes (69) being the most attractive. Poroplastic materials allow a water solution to be retained in their network and have been proposed as a replacement for bubblers (67), but they are still under investigation.
- *Solid sorbents (other than charcoal):* Although charcoal has gained the status of the almost universal solid sorbent, it has some limitations (sensitivity to humidity, reactivity with some chemicals, etc) which have promoted the development of other sorbents (7, 10, 42). Silica gel or porous polymers, such as Tenax, XAD, Chromosorb, Porapak (coated sorbents), etc, may present some advantages over charcoal under some circumstances and for some solvents, but for some of them validation may be more difficult due to performance variations between batches (25). Recovery of the solvent from these solid sorbents can be achieved by liquid extraction or by thermal desorption. Both techniques have different advantages and

limitations that determine the final choice of the desorption method.

- *Miscellaneous:* Other methods are possible, such as condensation by freezing out the solvent vapors (and also the water!) or the use of impregnated papers, but they concern limited and specific applications. Figure 3 shows different sampling methods used under real field conditions.

Analytical methods

The analytical methods presented have been taken from reference 14.

Gas chromatography. Gas chromatography (GC) is without a doubt the most widespread analytical method for solvents. It has developed very much over the last decade, and the introduction of capillary columns has increased drastically the separation capacity compared with the conventional packed columns. The most usual detectors are the flame ionization detector (FID) (almost universal) and the electron capture detector (very sensitive to halogenated hydrocarbons). But others, such as the photoionization detector (PID), the nitrogen phosphorous detector, the flame photometric detector, the infrared detector (with Fourier transform) may in some cases present advantages of sensitivity and/or specificity.

Mass spectrometry is becoming the detector of choice since it allows the chemical species to be identified, but due to its price its use is still restricted to well-equipped laboratories.

Technological progress has contributed to the improvement of the performance of the gas chromatographic method by solving a series of problems, such as reproducible injection into capillary columns, valve switching for backflushing or for selecting a portion of the eluted substances, interfacing with a mass spectrometer, etc. The introduction of microprocessors for controlling the functions of the instrument, for storing and data processing (integration, statistics, etc), or for controlling automatic and continuous processes completes this development.

Liquid chromatography. Liquid chromatography complements the gas chromatographic method for organic solvents which are too reactive to be separated in the gas phase. In such cases sampling with bubblers for instance allows the solvents to be transformed into more stable species adapted to the detection technique used. This technique was not used however very much until the introduction in the mid-1970s of high-performance liquid chromatography (HPLC). The detectors used are of different types, but the most widespread are the spectrophotometers at a fixed wavelength in the ultraviolet range or at a variable wavelength in the ultraviolet-



Figure 3. Operator equipped with a charcoal tube (inside a plastic holder), a badge, and a filter cassette. Beside him a sampling system with conventional impingers to collect ethanalamine.

visible range. Spectrofluorimeters may increase the selectivity and sensitivity of the detection for some compounds.

Recently the ion chromatographic technique, mostly used for anions, has been improved and has shown to be an interesting alternative for solvents easily transformed into ionic species.

Spectrophotometric methods. Spectrophotometric methods, already discussed in the preceding section, are still in use when chromatographic methods are not appropriate or not available. Special techniques such as chemiluminescence (53) or tunable atomic line molecular spectroscopy (26) belong to the research and development field.

Other methods. Organic solvents cover such a broad range of chemical species that almost all analytical methods could be considered. Thus, X-ray analysis has been proposed to localize and quantify solvents adsorbed on charcoal tubes (40).

Direct-reading instruments

Direct-reading instruments represent a very important tool in occupational hygiene for a quick overview of the situation rather than for an evaluation of worker exposure. Very few such instruments have been adapted to personal sampling, but they are so widespread and so widely used (too often by non-specialists), due to their simplicity, that they have been used to evaluate the worker exposure also (too often abusively).

Colorimetric instruments. Colorimetric instruments include the famous detector tubes that exist for more than 200 substances; they allow an exposure evaluation to be made if a sufficiently large number of spot samples (1–2 min) are taken (39). A few have been developed for long-term and personal sampling (8 h).

Passive sampling with detector tubes or colorimetric papers work for some gases and vapors (54). Their advantages are their simplicity and low cost, and their disadvantages are their limited shelf life (not for all) and their lack of specificity since, for many solvents, the same colorimetric reaction is used.

Multipurpose detectors. Table 4 summarizes very roughly the advantages and limitations of the most common nonspecific detectors. For those adapted to continuous measurement, evaluation of exposure becomes possible in simple situations where a single solvent is used (no interference) at a sufficiently homogeneous concentration, allowing sampling at a fixed location (no need for personal sampling). Infrared detectors equipped with a wavelength selector are the only ones possessing some specificity.

Specific detectors. For some gases specific detectors have been developed but not for solvents. Portable gas chromatography (with FID or PID) belong to this category but are still rather large. A pocket size gas chromatograph has been under development for a long time (41). Portable mass spectrometers have also been brought out for industrial hygiene applications (43). Automatic periodic sampling or semicontinuous measurement can be adapted to gas chromatography or to colorimetric reactions (continuous flow). In the chemical industries, investigators have already taken advantage by combining the new development in different fields (solid sorbents, column switching, automation, microprocessor, miniaturiza-

tion, etc) to build highly specific and highly sensitive monitors. Widmer et al (65) developed such instruments for substances with low permissible levels such as dimethylsulfate (TLV = 0.1 ppm), epichlorohydrin (TLV = 2 ppm) and bis(chlormethyl)ether (TLV = 1 ppb).

The correct use of all these instruments requires good knowledge of the instrument itself (working principles, performances, limitations, checks and calibration requirements, etc) and a good professional attitude and common sense. Therefore to avoid misuse and misinterpretation of results nonspecialists should not use them. Good control of these instruments makes also extended applications possible, such as the detection of styrene by a mercury "sniffer" (24) or the detection of halogenated hydrocarbons by an ozone monitor (22).

Interpretation of results

Quality control has developed greatly in the last decade as a consequence of a growing awareness of the unreliability and incomparability of too many analytical results (with possible serious consequences), and it is becoming a very important part of the control of results. Calibration, validation, and internal and external (interlaboratory) checks are part of quality control programs which should be promoted by methods standardization, by rules such as "Good Monitoring Practices" (5, 58), and by accreditation of occupational hygiene laboratories.

Table 4. Advantages and limitations of direct-reading instruments.

Type	Advantages	Limitations
Explosimeters	Portability Battery-operated For safety problems	Not very sensitive Not convenient for continuous reading
Flame ionization	Sensitivity Stability	Cumbersome Need of gases and an alternating current power supply
Photo ionization	Portability Battery-operated Sensitivity	Not sensitive to a few gases or solvents
Infrared	Specificity Sensitivity	Cumbersome Need of alternating current power supply No linear response (old models)
Coated piezoelectric crystals	Still under development ^a	

^a See reference 33.

Table 5. Complementary useful information related to workers' exposure.

Job	Exposure	Methods (sampling, analysis)	Personal information
Name	Time (during a day, a week, etc)	Type	Preceding job
Type	Protective equipment	Purpose	Life-style (smoking, drinking, etc)
Products	Rotation	Location	Medical information
By-products	Effort needed	Period	
	Actual permissible levels	Quality control	

Computers and their almost unlimited memory capacity help to process (integration, adjustment to temperature and pressure, etc) and accumulate data on exposure measurements and offer future epidemiologic studies a more reliable basis than earlier. Table 5 lists some important information related to worker exposure that should be recorded along with the results of the exposure measurements and that should be taken into consideration in the interpretation of results.

Many other relevant aspects have been discussed or mentioned in the sampling strategy section of this paper. A few relevant sources of error follow:

- Contamination of samples during storage or shipment may be overlooked in some quality control programs (9, 17).
- The survey may modify the real usual field conditions in a much more important way than usually imagined, which will bias the results.
- Solvents induce, in chronic exposure, behavioral effects and personality changes (38, 56); does this phenomenon change the exposure pattern with time? Addiction, in the same way, may transform an occupational exposure into a voluntary "sniffing" habit.
- Clothes contamination may bias the sampling and increase absorption through the skin.
- Many other sources of error are possible.

Statisticians can also be of great assistance to the correct "manipulation" of results by seeing that appropriate statistical tests are applied.

Conclusions

Although the objective of this paper was the presentation of air measurements (also called ambient monitoring) to assess exposure to solvents, I cannot conclude without mentioning biological monitoring as another valuable complementary approach. A discussion on the advantages and limitations of both approaches is beyond the scope of this paper, but it should be stressed that the choice of the method used depends on many different factors and is far from being evident.

Knowledge and instrumentation have now arrived at a point where reliable exposure measurements can be performed. In the near future portable specific monitors fulfilling all the requirements discussed will probably be developed. This development does not mean that proper protection can now be provided for a worker's health since the relationship between exposure and effect is not yet well established for many solvents. As long as this necessary basis is not available, risk assessment leading to sound permissible levels will not be possible. Moreover, long-term toxicity (especially the mutagenic or cancerogenic properties) of many solvents should be more exten-

sively studied. Knowledge in this field grows less rapidly than technological changes do and also less rapidly than the number of new solvents introduced onto the market. Effort has to be made to reverse this situation by promoting occupational hygiene and by recognizing the multidisciplinary science of exposure assessment and the need for professionals in this field.

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