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A Review of Video Exposure Monitoring as an Occupational Hygiene Tool

G. ROSÉN[1], I-M. ANDERSSON[1], P. T. WALSH[2]*, R. D. R. CLARK[2], A. SÄÄMÄNEN[3], K. HEINONEN[3], H. RIIPINEN[4] and R. PÄÄKKÖNEN[4]

[1]*National Institute for Working Life, SE-113 91 Stockholm, Sweden;* [2]*Health and Safety Laboratory, Harpur Hill, Buxton SK17 9JN, UK;* [3]*VTT Technical Research Centre of Finland, PO Box 1307, FIN-33101 Tampere, Finland;* [4]*Tampere Regional Institute of Occupational Health, PO Box 486, FIN-33101 Tampere, Finland*

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This study reviews use of video exposure monitoring (VEM, also known as PIMEX) as an occupational hygiene tool since its inception in the mid-1980s. VEM involves the combination of real-time monitoring instruments, usually for gases/vapours and dust, with video of the worker's activities. VEM is an established method used by practitioners in different countries. The technical aspects of these VEM systems are described, then applications of VEM are discussed, focussing on task analysis, training (risk communication), encouraging worker participation in and motivation for improvements in the workplace environment and occupational hygiene research. The experiences from these applications are used to illustrate how exposure visualization with video can act as a catalyst, initiating a change process in the workplace. Finally, the role of VEM as a workplace improvement tool, now and in the future, is discussed.

Keywords: exposure visualization; PIMEX; real-time monitoring; risk communication; task analysis; video exposure monitoring; workplace improvement strategy

INTRODUCTION

Many workers are still exposed to hazards even though knowledge about risk and control measures is well established. Exposed workers commonly accept their situation as a natural and necessary part of their work, and believe that controls are unnecessary. While most managers understand the risks associated with their processes, they (and occupational hygienists) often only have a limited understanding of when and/or where exposure occurs. This is especially true in small to medium size enterprises (SMEs) (Walters, 2001).

The European Commission's community strategy on health and safety at work 2002–2006 (European Commission, 2002) states that health and safety in workplaces is based on preventive approaches, bringing in all players, including the workers themselves, with a view to developing a genuine culture of risk prevention. This view is based on the awareness that successful preventive risk control in workplaces is mainly the result of open collaboration between the 'owners' of the problem—the exposed worker, the manager and the work environment expert. There are too many examples of costly investments in control measures with a limited effect because of insufficient communication between the partners. For example, investments are made in ventilation systems to reduce workers' exposure to air contaminants without ensuring that its use is understood by the worker. In addition, while the worker may fully understand the hazard control technology, it may not be practicable to utilize it in the intended manner. Similar situations may of course apply to noise control, prevention of musculoskeletal disorders, etc.

It is often possible to reduce exposure if some basic facts about the nature of the hazard are better understood by the exposed worker, e.g. the emission and transport of air contaminants from the source to the worker's breathing zone, how the contaminant may or may not be captured by an exhaust. Such facts are well described in textbooks (e.g. Rosén, 2001a) and experts are well aware of this. The workers, however, usually do not possess this knowledge.

*Author to whom correspondence should be addressed.
Tel: +44 (0) 1298 218541; fax: +44 (0) 1298 218395;
e-mail: peter.walsh@hsl.gov.uk

The workers' knowledge of risks associated with their tasks and, perhaps more importantly, how these risks can be controlled, is essential to improve their health. Traditional ways of disseminating this knowledge via training classes or leaflets etc. very often have a limited effect (Svensson *et al*., 2004). More powerful training tools are therefore needed in this context. Moreover, the possibilities for distance learning need to be improved because of the limited time available for such training activities.

Implementation of technical control measures also has a psychological dimension. It is not always sufficient that the worker can use the equipment and understand the basic principles; the solution must also be accepted. A participative approach when planning for control measures is, therefore, necessary to bring about an effective solution. Similarly, this approach is important not only for the problem solving part of the control process but also for problem identification. The more the workplace staff are involved, the better the chances that knowledge acquired from this collaboration will generate good results.

It is, therefore, apparent that there could be significant savings, when risk assessments prescribe reduction measures, if the expert knowledge in hazard control can be brought together with the workplace expertise. Key factors here are the motivation and commitment of the workforce. It is, therefore, a high priority that such tools for the expert to facilitate this communication are developed and made more widely available. The potential of visualization tools to involve exposed workers in the control of hazardous agents in workplaces was discussed in an editorial in this journal (Rosén, 2002). The principal message stated here was that the time had come for such visual techniques, developed over the last two decades, to become more widely available.

In this paper we review exposure visualization methods where video and exposure monitoring using real-time (direct-reading) instruments have been combined. We discuss some of the more important developments, in our opinion, in video exposure monitoring (VEM) comprising different technical solutions, strategies for their use and, especially, results and experiences from their application. Real-time monitoring instruments alone are, of course, powerful tools for the expert, but to add synchronized video recording can add substantial value, especially since it can enhance effective communication of the results between the involved partners. VEM is a useful tool for improving motivation and commitment to risk awareness and reduction. It is also a powerful tool for occupational hygienists for (a) workplace analysis and (b) developing their own talents in the understanding of the link between exposure and the workplace environment.

A number of visualization methods utilizing only video are also used in the workplace for hazard identification and control. We have, however, limited this review to methods combining real-time monitoring instruments (particularly for gases, vapours and aerosols) with video, permitting immediate or later analysis of the results, for occupational hygiene use. Ergonomic, physiologic or dermal exposure applications, for example, are not covered.

BASIC CONCEPT

In the early 1980s, low-cost video cameras became available in the consumer market and real-time monitoring for occupational hygienists was already in use. Many hygienists using such monitoring instruments realized their potential but their use was mainly limited to direct reading from the display or connecting the instrument to a recorder that produced concentration–time graphs. At that time the instruments were, in general, not equipped with any data logging facilities. A typical problem arising from later analysis of the data was that reasons for peaks in the measured values were difficult to explain, even if the exact time of occurrence was known. The hygienist was normally too busy performing the measurements to write down all the facts that might influence the measured value. Some hygienists simply displayed the concentration–time profile as a wallchart and encouraged the staff to discuss and try to explain reasons for the results. This was excellent in motivating and engaging the workers to participate in the problem solving process but it left many unanswered questions—the answers to which could have been important.

Occupational hygienists needed a strategy for using real-time monitoring instruments in a more informative way. The National Institute for Working Life (NIWL) in Sweden discussed the possibilities of linking video recording with real-time monitoring instruments for exposure measurements, i.e. to manipulate the video signal from a camera so that the analogue output signal from the instrument was presented graphically in the video picture. Such equipment was on the market, but for another application, displaying the output value as a black and white double arrow on a vertical scale in the picture. The first practical trials were made in a woodwork establishment, studying exposure of spray painters to organic solvents. The end of a long sampling tube was located in the worker's breathing zone and the sample was pumped to a photoionization detector (PID) connected to the rest of the equipment. The value of this arrangement for the occupational hygienist as well as for the worker was immediate and obvious (Rosén and Lundström, 1985; Rosén and Lundström, 1987).

The first version was soon replaced by a specially developed system displaying the exposure data as a bar graph in the video picture (Rosén and Andersson, 1989). The method was given the name PIMEX, (Picture Mix and Exposure). It was commercially available for a limited period (1985–2000) as the IBC PIMEX and IBC miniPIMEX.

NIOSH researchers (Gressel *et al*., 1987, 1988) also described a technique using a video overlay board and computer program to display, in real-time or after recording of data and video on tape, the measured value as a bar graph and the picture on the computer screen. Their first tests were made with a light scattering instrument measuring dust exposure during manual weigh-out of acrylic copolymer powder and during cast cleaning in a foundry. VEM was a new system to organize, analyse, and present information in a unique way. Their experiences were similar to those of the Swedish group: the clear advantage of being able to show graphically to management and workers how the workers' activities and practices can affect their exposure. The NIOSH group used the name Video Exposure Monitoring for their method (Gressel *et al*., 1993; Heitbrink *et al*., 1993). A detailed description of their system is given in Gressel and Heitbrink (1992). Subsequently, other implementations of VEM appeared. These are discussed in the following section.

ALTERNATIVE IMPLEMENTATIONS

The alternative and later implementations of VEM have many features in common, principally the use of digital technology to process and display the video and real-time exposure data on a PC. The following (non-exhaustive) list illustrates the main features of the principal systems, in our view, which are currently in use, in addition to those mentioned above. It should be noted that many of these systems are under continuous development as technology advances rapidly. Consequently, the current implementations may have changed since their published descriptions.

PIMEX-PC (NIWL, Sweden)

NIWL has developed a technique based on a standard computer and specially developed software (Rosén, 2001b; Andersson *et al*., 2002; www.arbetslivsinstitutet.se/pimex). The software is written in Labview® (National Instruments). Two versions of the software are used: one is for collection of video and data where the picture from the video camera and data are presented on computer screen in real-time and stored on hard disk. The other version is for replay of video and data. Both versions can present data digitally, as a bar graph or a line graph. The replay version displays the line graph with data from a full period. A pointer on the line graph is synchronized with the video file and can be moved to any point (time) of interest. After commencement of the video replay, the pointer follows the synchronized video picture. Display of data in digits, as a bar graph or as a line graph is optional. Figure 1 shows a typical result window from the replay version of the

Fig. 1. Example from a PIMEX-PC recording. The video picture window shows a person welding and carrying a monitoring instrument for fume in a backpack. The graph window to the right shows how the welder's exposure to welding smoke has varied during the period. The bar graph to the left shows the instantaneous exposure level.

program. It is possible to export data to spreadsheet programs such as Excel® for further analysis.

Exposure Level Visualization—ELVis (HSL, UK)

The Health and Safety Laboratory (HSL) UK has continually developed an in-house exposure visualization technique (Gray *et al*., 1992; Unwin *et al*., 1993; Walsh *et al*., 2000; www.hsl.gov.uk/case-studies/visual.htm) since the original commercial VEM system (i.e. IBC PIMEX). These developments were stimulated by the need to improve the technology and the requirement to carry out quantitative analysis of exposure coupled with detailed task analysis. By the mid-1990s, personal monitors were shrinking in size and often included on-board data loggers with digital outputs. Digital radio telemetry was available in the form of easy-to-use and reliable radio modems. Data logging could be implemented on portable PCs, which also had multimedia and video options.

The current system 'ELVis' (Exposure Level Visualization) is a modular PC-based exposure Visualization tool written in C++. A screen grab is shown in Fig. 2. It enables digitized video and exposure data to be mixed and displayed on a PC. Data can be averaged over any period, which is useful for investigating trends in the TWA and filtering particularly spiky data when attempting to detect changes in exposure. Data can be labelled in a hierarchical, Gantt chart style. The tool automatically calculates peak exposure concentration, percentage of total time and percentage of total exposure on a particular task. Examples where the technique has been applied are given in the Applications section.

Both DVCAM and MiniDV tapes are used for digital video (DV) recording. Video can be digitized using an MPEG1 capture card; MPEG1 combines small file size with good quality. Most computers can display MPEG1 files without having to resort to installing special registration keys (codecs). DV Firewire can be used for transfer of video to computer; however, files are generally too large and unwieldy to be considered for clips beyond a few minutes. Technical developments are, however, very rapid and will overcome this limitation. Distribution on CD limits the footage to a few minutes compared with ~80 min obtained using MPEG1. Software is available to encode DV to MPEG1 but this takes a powerful machine and a lot of time. A capture card is currently a more cost-effective route. Recordable DVD is also a medium with potential for archiving and presentation of VEM results.

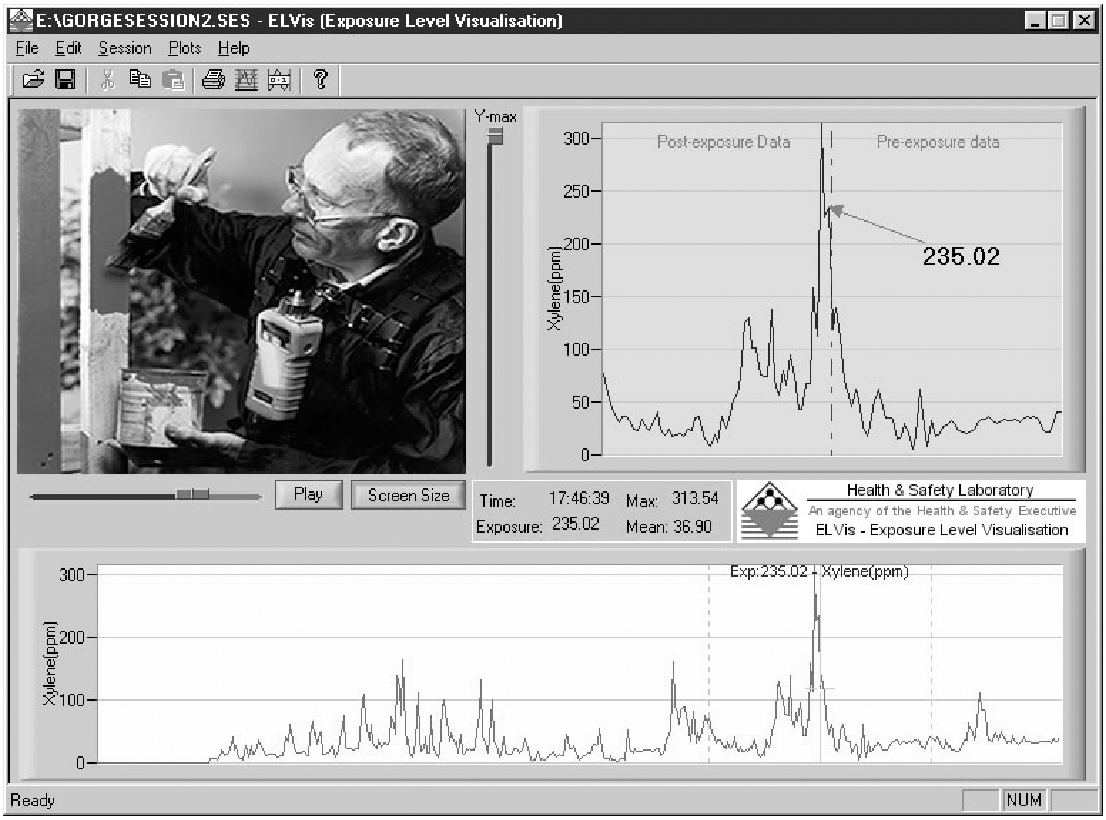

Fig. 2. ELVis screen-shot.

FINN-PIMEX (VTT, Finland)

The FINN-PIMEX system was developed at VTT Technical Research Centre, Finland during 1996–1999 (Heinonen and Säämänen 1999, 2000). The FINN-PIMEX equipment was, like ELVis, developed to enhance the analysis properties of the original VEM system. The measurement signal is stored in a database and the video image is stored with the S-VHS tape recorder. The computer used in the system is equipped with a video capture card and data acquisition card. The system can also be used with measuring equipment using RS 232 data transmission channel. The video cassette recorder is equipped with a time code generator and RS 232 serial port. The measured data and video image are synchronized with a time code generated in the video cassette recorder. Any video camera producing S-video signal can be used.

The system has been designed to facilitate subsequent analysis. The user can classify working tasks and use marking tags for special events or annotations. These entries are stored in the database and the user can utilize these properties either during the measurement or in the analysing phase after the measurement has been completed. It is also easy to make fast searches of the data using different types of criteria (e.g. signal level, user classification, marking tags). The computerized system automatically searches the video tape for the frame corresponding to the search criteria, and then shows the video image. The measured data is read from the database and shown in the graphs (bars and time series) simultaneously with video image (see Fig. 3).

CAPTIV (INRS, France)

The CAPTIV system (Centrale d'Acuisition au Poste de Travail Informé par Vidéo) was developed at the Institut National de Recherche et du Sécurité (Martin *et al*., 1999). The system consists of a personal computer equipped with an analogue/digital data acquisition board, a video capture card, a video recorder and suitable CDD video cameras. The video signal is digitized in real-time and displayed in the user interface window. Simultaneously, video images are recorded on a video recorder with a time code generator. The video recorder can be controlled with serial interface (RS232C) and all the standard video sequence search functions can be used. The sensor signals are sent via a telemetry link to the data acquisition board.

The CAPTIV program consists of two main modules: data acquisition and workplace analysis modules. During the data acquisition, the information from sensors is presented in the form of a time series and the video window is active. A characteristic feature of CAPTIV is the ability to adjust the time offset caused by the finite response time of the detector. A multimedia database enables searches to be performed based on user-set criteria. In the workplace analysis mode, specific periods, such as interesting work tasks, can be searched and viewed. A number of signal processing tools are available to assist data analysis, e.g. the ability to identify a peak or a group of peaks higher than the specified value of the background threshold (termed an 'emergence'). Any emergence can then be identified and classified.

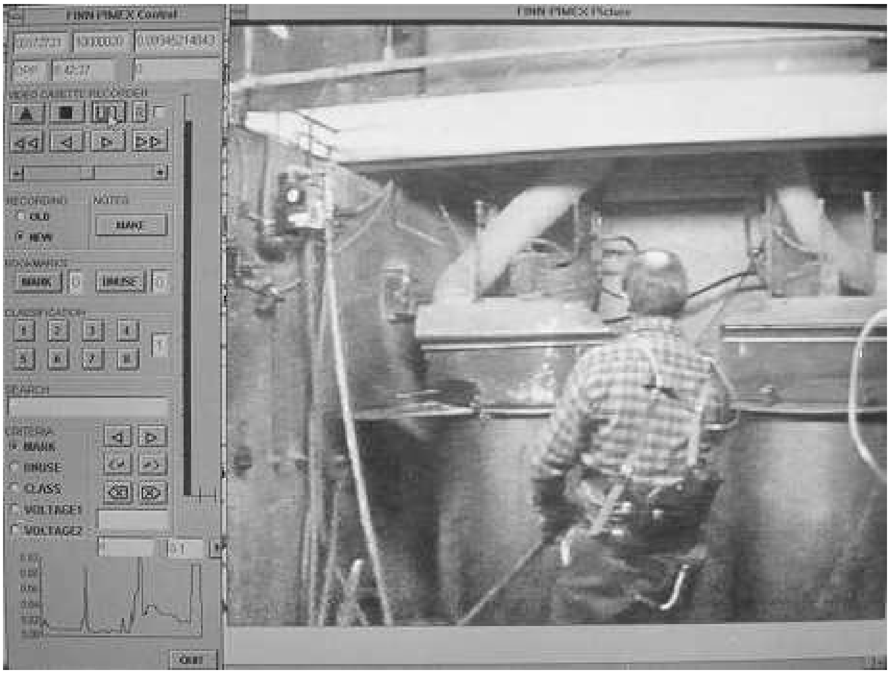

Fig. 3. FINN-PIMEX screen-shot.

KOHS PIMEX (KOHS, Austria)

This system is commercially available (see www.pimex.at). Currently, an IEEE 1394 (Firewire) video system is used and the video component of the KOHS PIMEX software is capable of handling several different video sources. Video and measurement data are compressed in real-time on the main system. After recording a sequence, the VEM observation is stored and ready for display immediately. Several inputs can be measured within one VEM observation. For example, three particle size fractions of dust can be measured in real-time synchronously with the heart rate which is recorded using a special non-invasive bio-monitoring device. To help maintain commitment to the improvement process in an establishment, based on intervention studies using KOHS PIMEX, VEM material and suggestions for improvement can be recorded on a CD-ROM and provided to the company immediately following the study.

VEM (USA)

Since the early efforts of NIOSH researchers to develop and promote VEM as a tool to evaluate and protect workers, further developments have taken place at NIOSH (Kovein, 1997) and Purdue University (Xu and McGlothlin, 2003). The Purdue University system has evolved to use completely wireless video and environmental sensors that can be captured, analysed and sent anywhere in the world through secure internet systems.

GRIFFITH PIMEX (Griffith University, Australia)

A VEM system has also been developed at Griffith University, Australia (Bromwich, 1995). The original system recorded noise exposure data stored on the audio track of a video camcorder. The audio was analysed using the PC's sound card and overlaid on the video image as a frequency spectrum using a video overlay box. This approach permitted some post-exposure manipulation of the data. The current Griffith PIMEX system integrates data acquisition, logging and digital FM telemetry on a single circuit board. The system permits up to six channels of data to be telemetered from a backpack which monitors instruments such as a MIE MiniRAM or a HNU PID, pulses from a Polar heart rate belt and thermistors. The video data from a webcam is compressed in real-time on a laptop computer, allowing many hours of recording to its hard drive.

TECHNICAL ASPECTS

General

VEM requires the combination of a real-time monitor synchronized with a video record of the worker's activity. The video and monitor data can be displayed in real-time and/or stored and processed for analysis and display later. The two most critical aspects of synchronization are:

- the need for a monitor with a fast response time to follow fluctuations in exposure; and
- synchronization between the frame numbers or the clocks on the video and real-time monitor to allow correct interpretation of the relationship between an activity or event and exposure. This is linked to the first point above because any delay in response time must be considered in the analysis: the faster the response time the easier the interpretation of the results.

The monitor's response will cause the activity to lag due to:

(a) the monitor's response time (characterized by the monitor's time constant which can be measured in the laboratory)—composed of the time taken from the sampling point to the sensor itself and the inherent response time of the sensor; and
(b) the time taken for the agent to disperse from the source to the monitor, placed near the worker's breathing zone (characterized by the process time constant which may possibly be estimated through knowledge of the process).

Gressel *et al*. (1993) and Martin *et al*. (1999) describe the simple technique of shifting the monitor data with respect to the video time to account for the monitor lag. However, some distortion of the actual concentration profile will occur if the time constant of the monitor is similar or greater than that of the events under investigation. Heitbrink *et al*. (1993) discuss the analysis in greater detail including multiple regression, autocorrelation and time series analysis to attempt at deriving a meaningful relationships between, typically, the exposure concentration and explanatory variables describing workplace events.

Other aspects that need to be considered are the ergonomics of wearing monitoring equipment with the objective of minimizing its effect on the worker's activity. In the early days of VEM, this was more of a problem because of the larger size and weight of the monitors. However, technology has progressed considerably since the original equipment was first developed. While the types of sensors have not changed over this period, advances in electronics have resulted in considerable reduction in the size and weight of monitors, allowing the equipment to be less intrusive. Additionally, the use of digital techniques has made data communication and processing much faster and more reliable and the measurement process (e.g. calibration) more accurate. The various technical components and measurement techniques of VEM are now discussed in detail.

Real-time monitors

Gases and vapours. Most applications of VEM involving vapour measurement have employed the PID (e.g. MiniRae, www.raesystems.com; for general information see Woebkenberg and McCammon, 1995; Evans *et al.*, 2001) because it responds to a wide range of VOCs (i.e. those having photoionization energies of <~10.6 eV) and having a fast response time. Typically, instruments are available with response times <2 s (Simpson *et al.*, 2003). The user should, however, be aware of possible interferences and environmental effects such as variations in humidity, temperature, etc. which will affect the accuracy of the measurement.

Examples of applications of PIDs for VEM are:

- solvents and formaldehyde from surface-coating operations in the woodwork industry (Rosén *et al.*, 1990);
- styrene from laminating in boat building industry (Andersson *et al.*, 1993);
- gasoline vapour at service stations (Cook and Kovein, 1997);
- tetrachloroethylene from dry-cleaning machines (Earnest, 2002);
- solvents in a university pharmaceutical laboratory (Xu and McGlothlin, 2003);
- formaldehyde (using methanol as surrogate) in an anatomy laboratory (Ryan *et al.*, 2003).

Generally, the response of the PID is interpreted qualitatively and the concentration commonly referred to as an isobutylene (isobutene) equivalent concentration because isobutene is predominantly used to calibrate the monitor. However, if quantitative measurements are required then calibration with respect to a specific gas/vapour being monitored is sometimes possible. For example, in certain cases there is essentially only one gas present to which the instrument is responsive, e.g. monitoring tetrachloroethylene (perchloroethylene) in dry cleaning establishments (Earnest, 2002; Walsh *et al.*, 2002). As a check, samplers (pumped or diffusive, although the latter are less intrusive) can be placed adjacent to the PID to provide a measure of the TWA concentration.

Infrared monitors have also been used to visualize exposure to nitrous oxide. While the current infrared monitors are not as fast as the PIDs used in VEM (typical response time of at least several seconds), they have been successfully employed. Gressel and Heitbrink (1992) and Crouch *et al.* (2000) monitored in the breathing zone of dentists using a sample line attached to a bench-mounted (i.e. transportable) infrared analyser (MIRAN 1A or 1B2, Thermo Electron Corp.). Also, the effects of patient behaviour and controls on exposure of dentists to nitrous oxide were investigated using ELVis (Guiver and Plant, 2003) in various dental surgeries in the UK using a personal infrared monitor (www.bacharach-europe.com).

A VEM system based on a portable flame ionization detector (FID) has been used to monitor styrene vapour exposure in the manufacture of glass fibre reinforced polyester products (Säämänen *et al.*, 1993).

The VEM technique has also been used in public health applications: Hakkola *et al.* (2000) compared customer exposure to gasoline vapours at two types of service stations.

Carbon monoxide electrochemical sensors were tried for a VEM study of a sausage smoking factory but were found to be too slow (Rosén and Lundström, 1987). The response time of the sensors used was of the order of 30 s.

Aerosols. Usually dust concentrations in the workplace air (expressed in units of mg m^{-3}) are measured with a portable dust photometer (e.g. DATARAM PDM-3, MIE Inc., www.thermo.com; HAM, PPM Inc., and for general information see Pui and Swift, 1995; Maynard and Jensen, 2001). This dust monitor is based on the detection of the forward scattering of pulsed near infrared (ca. 880 nm) light from dust particles passing through an open sensing chamber. The technique's sampling profile approximates to that of the upper end of the respirable fraction (Maynard and Jensen, 2001). The SKC Split 2 monitor (www.skcinc.com) was, however, found to be particularly suitable for the measurement of solder fume because of its smaller and more open sampling volume compared to the Dataram (Dowker *et al.*, 2004). Also, Hund aerosol monitors (www.hund.de) have been used in the KOHS PIMEX system.

The advantages of the above type of monitor are its lightweight and the compact size suitable for personal sampling from the lapel or chest. The disadvantage is that the response time of the monitor depends on the transportation of air to the sensing chamber. However, normally the air circulation near the worker (convection, air currents, and personal movements) is high enough. Another disadvantage in the use of light-scattering photometers is that the calibration may change with the composition and size distribution of the particles (Pui and Swift, 1995; Thorpe and Walsh, 2002)

Examples of applications of portable dust photometers in VEM are:

- acrylic powder in a plastic manufacturing plant (Gressel *et al.*, 1987; Gressel *et al.*, 1988; Gressel and Heitbrink, 1992);
- brake dust during automotive servicing (Gressel *et al.*, 1988);
- foundry fume from casting in a pilot foundry (Gressel *et al.*, 1988);
- mechanical scaling in a mine (Andersson *et al.*, 2003);

- wood dust in furniture industry (Andersson and Rosén, 1993; Kulmala *et al*., 2000);
- dust exposure in thermal insulating work (Saarenpää *et al*., 1994);
- machining dust and metal working fluid mist exposure in high speed machining (Kauppinen *et al*., 1994);
- evaluation of LEV for foundry casting-cleaning (Gressel, 1997);
- flour dust exposure in bakeries (Enbom and Säämänen, 1998);
- rubber fume from autoclaving in rubber industry (Walsh *et al*., 1999);
- nickel sulphate aerosol in electrolytic nickel refining (Kulmala and Säämänen, 2000);
- solder fume in electronics industry (Dowker *et al*., 2004);
- silica in slate-splitting (Walsh *et al*., 2000; and see Applications section).

Dust monitors are usually calibrated with reference to the TWA measurement from a cyclone sampler immediately adjacent to the monitor or, possibly, using a pumped system where the sampler is immediately downstream from the real-time monitor. Such flow adapter kits for concurrent filter collection are usually available from the manufacturers. The use of a pumped system, however, may affect the calibration because the change in flow characteristics may alter the particle size distribution. It is also possible to derive quantitative values for a particular component of dust in order to provide a real-time profile of the concentration of that component. For example, VEM measurements on stonemasons and slate splitters were performed where the response from the MIE DataRam was calibrated in terms of the respirable silica concentration as derived from x-ray diffraction analysis of the respirable fraction sampled on a Cyclone sampler (Walsh *et al*., 2000). This was achieved by comparing the TWA response from the instrument with the concentration of respirable silica obtained from the Cyclone sampler. This assumes that the composition and size distribution of the aerosol remain constant over the measurement period and will be process dependent.

Some limit values are expressed in terms of the inhalable concentration rather than the respirable (alveolar) concentration, e.g. flour and wood dust. Again it is possible to calibrate the response of the monitor using an inhalable sampler, e.g. IOM head. The assumptions made are that the ratio of the quasi-respirable fraction, as determined by the response function of the monitor, and the inhalable fraction, as determined by the sampler, remains constant over the measurement period. The constancy or otherwise of this ratio depends on the dust generation process. The results should still, however, be interpreted with care, when used to measure the inhalable mass concentration, as the sensitivity to equivalent aerosol masses represented by 20 μm particles is approximately a factor of 100 lower than the sensitivity to 2 μm particles (Maynard and Jensen, 2001).

If the particle concentration to be measured is very low, e.g. in clean room conditions in a pharmaceutical factory, the sensitivity of the above types of aerosol photometer is also very low. In these cases, optical particle counters (see e.g. Pui and Swift, 1995) can be beneficial. In optical particle counters, the individual particles are carried through the viewing volume by an air stream. The viewing volume is illuminated with (laser) light and the light scattered from the single particle is detected with a photodetector. However, particle counters are currently not suitable for personal monitoring.

The optical particle counter (Met One, www.metone.com) connected to the FINN-PIMEX system has been successfully utilized in a pharmaceutical factory, in an operating theatre and during the injection moulding of plastic items. The system has also been used to determine particle release from different surgical fabrics (Nurmi *et al*., 2003). The instrument was used in the continuous mode where the total particle count (all particles >0.3 μm) was obtained every 3 s. Normally, this gives enough sensitivity to be utilized in VEM. However, the method also has some disadvantages. The updating frequency of the particle count is quite long and can cause some difficulties in interpreting the results. Normal post-calibration methods such as conventional occupational hygiene sampling cannot be done, but the relative variation of particle counts can be easily obtained from this system.

Personal monitoring of environmental levels of aerosols for environmental studies (e.g. for ultrafine particles), including investigating exposure of workers who spend a lot of time outdoors, also requires more sensitive monitors. Here hand-held particle counters can be employed, based on Condensation Nucleation (or Particle) Counter, CNC or CPC, using alcohol as the medium to grow the dust particles into droplets to be counted by the laser detection system (e.g. TSI P-Trak; www.tsi.com; for general details see Pui and Swift, 1995). Such a detector has been used for VEM of ultrafines in the outdoor environment (Arnold *et al*., 2004).

Other technical aspects

Synchronization. On systems such as PIMEX-PC synchronization is automatic since every data point is linked to the corresponding video frame. Otherwise, synchronization of the video with the real-time monitor signal is crucial for correct interpretation of the data. There are various ways to ensure that synchronization is achieved. A simple synchronization method is to use the time registered in the video cassette (e.g. time code) together with the time-stamped data from the real-time monitor. Alternatively, the monitor display showing the monitor clock can be videoed. This provides a reference for synchronization. Ideally, the clocks should be checked at regular intervals over the monitoring period as some clocks can drift, resulting in a variable offset correction. A reference clock can be used to set both the video and data logging clocks to a standard time. Another synchronization method includes using a calibration gas, e.g. 100 p.p.m. isobutene, for VOC monitors. Filming the application of a calibration gas to a monitor provides a mark in the data that can be used for synchronization (a 'visual clapperboard'). The clocks need to be accurate to within a few seconds if they are solely being relied upon for synchronization over an extended monitoring period of a few hours.

Video camera. Any video camcorder will suffice for VEM. Modern computers together with digital video (DV) camcorders provide easy transfer of video via a Firewire link. Other solutions for digitizing video are analogue capture cards for capturing video from non-DV camcorders. Webcams and USB communications are now satisfactory and cheaper options.

Telemetry. Analogue radio telemetry and radio modems are commercially available. However, radio modems (e.g. Satelline 2Asx, Satel Oy, Finland) are usually preferable for transmitting serial (RS232 usually), digital, real-time data from the personal monitors for display on a remote notebook or hand-held computer. However, they are sometimes subject to interference from other radio equipment and industrial equipment, which can cause loss of data. Kovein and Hentz (1992) describe the use of multiple radio transmitters and their application to VEM of methylene chloride exposure of a furniture refinisher. Video telemetry is also available commercially and could be appropriate for some hostile environments, e.g. asbestos removal.

Mounting of monitors. Various types of mounting systems have been used in VEM studies. The most common types are the backpack (see Fig. 4), holding the vapour/dust monitor with sampling tubes to the breathing zone of the worker, and the frontpack, positioning the dust monitor on the chest. Other designs have been used for more specialized applications. For example, because solder fume plumes are very localized and narrow the monitor has to be located

Fig. 4. Examples of instrument mounts for VEM: general purpose backpack, headset for solder fume monitoring, pushchair and pedal cycle for environmental monitoring.

as close to the nose and mouth as possible. A custom-built headset for solder fume monitoring using an SKC Split 2 aerosol detector has been used (Dowker *et al*., 2004), see Fig. 4, which addresses this requirement. Other examples of non-standard mounts for monitoring personal exposure to environmental pollutants are a baby pushchair (Arnold *et al*., 2004) and a modified pedal cycle (Clark, 2004), see Fig. 4.

Use in hazardous (potentially explosive) areas. Occasionally it may be necessary to monitor exposure to flammable solvents, e.g. in a spray booth. The risk assessment may require that equipment (electrical and materials) used within a hazardous area should be protected from explosion (Ex) and sparkproof. Some PIDs are typically certified for use in such hazardous areas, although other types of monitors are generally not certified and therefore could not be used in such environments. The video cameras typically used for VEM are not certified. Nevertheless, it is possible to obtain measurements of exposure in hazardous areas by using Ex-certified real-time monitors with on-board data loggers and locating the video camera outside the hazardous area. Synchronization would need to be addressed, as discussed above.

Display of exposure

The most commonly used means to display measured data on the screen is a bar graph, as data-time graph or digitally. The bar graph displayed beside or in the picture was the most common method used in the first systems because it was easy for anyone to understand, without experience of the interpretation of data from exposure measurements. The bar graph may be used in real-time as well as afterwards in post-processing. The data-time graph allows presentation of earlier data giving the viewer a better feeling of the periodic variation in measured values, e.g. a painter's exposure to solvents. One style of presenting real-time data in this way is in a scrolling window with data from, for example, the last minute filling the window. Previously recorded data can be presented in a similar way with, for example, a pointer moving along the graph synchronized to the video window. The data-time graph includes more information but the drawback is that the viewer may need a little more time to understand it. Digital display of data has been used only to a limited extent, and then often together with graphical presentation, because of the difficulties in reading and interpreting rapidly varying values.

The data-time graph when used to display the results following the completion of the monitoring session (i.e. post-processing mode, see also below) allows the viewer to see what will happen in the near future. They then have an opportunity to concentrate on the video when something special is about to happen (e.g. a sudden rise in exposure).

Post-processing of exposure and video data

The ability to link measured values, second by second in real-time, to events in the workplace allows one to investigate and explain reasons for increases in hazardous levels of air contaminants. This is an important option offered by VEM. The most basic calculations are of time-weighted averages, standard deviations and peaks for periods of interest. Analysis can be carried out by export to commonly used spreadsheet programs or as an integral part of the VEM system. Heitbrink *et al*. (1993) and Gressel and Heitbrink (1992) provide an overview of more detailed data analysis techniques, e.g. multiple regression, time series.

Normally-occurring variations in exposure levels imply that a significant proportion of the total TWA exposure during a work shift results from exposure peaks of only relatively short duration. For example, it was found (Andersson and Rosén, 1995) that for some tasks, almost 50% of the cumulative exposure (total dose) occurs in 10% of the total time for a variation in exposure corresponding to a GSD (geometrical standard deviation) of 3. These authors described how the detailed exposure analysis was performed using VEM data to provide a basis for prioritization of effective control measures. This type of analysis has also been incorporated, and made essentially automatic, in some of the workplace activities described in this paper.

APPLICATIONS

VEM has been used in the following areas:

- task analysis for understanding and controlling exposure;
- as a training aid for risk communication;
- to encourage worker participation in and motivation for improvements in the workplace environment;
- occupational hygiene research.

These applications are discussed further below.

Task analysis

The technique has been mainly used to provide quantitative and qualitative information on exposure for specialist occupational hygienists. The software and display techniques have been developed with this in mind. The following examples illustrate the use of detailed task analysis, which has been made possible with VEM coupled with a data analysis tool. Even with VEM task analysis tools, data analysis is a labour-intensive task but without it, analysis of the video and exposure data would take an extremely long time.

Glass fibre reinforced plastic (GRP) application in waste water tanks (styrene). For each piece of measurement data stored in the VEM computer file, the corresponding work task was determined from the video picture. Exposure data could, thereafter, be sorted according to the work step to which they are ascribable. With these data, each work step's duration and relative importance to total exposure could easily be calculated. Analysis of data from a spray booth in a plant producing waste water tanks in glass fibre reinforced polyester showed that more than half of the exposure was due to rolling with a metal roller. Surprisingly, work involved in trimming off superfluous, partially hardened material also made a large contribution to the total exposure. The sum of 46% of the total exposure was explained by 10% of working time (Andersson and Rosén, 1995).

Furniture industry (wood dust). The worker under study performed various manual carpentry tasks in a company which made specially designed interior fittings for offices, hotels and restaurants. The same analysis, as in the example above (waste water tanks), was performed and the result showed that routing with the hand-held power tool (milling) made the greatest contribution to exposure. The sum of 48% of the total exposure was explained by 10% of working time (Andersson and Rosén, 1995).

Slate splitting (crystalline silica). Previous surveys at a slate splitting plant in the UK indicated that some operators, particularly those actually splitting slate slabs are likely to be exposed to levels of respirable crystalline silica above the UK Medical Surveillance Threshold (0.075 mg m^{-3}). Personal exposures of slate splitting plant operators were monitored using VEM to examine the effect of LEV and LAD (local air displacement or air curtain/ shower ventilation) on exposure patterns (Guiver and Clark, 2002). Real-time monitoring was by PersonalDataRam (MIE Inc.). The instruments were calibrated on site using data from cyclone air samplers positioned adjacent to the PersonalDataRams, using the methodology in MDHS 14/3 (HSE, 2000). Samples were analysed gravimetrically for respirable dust and X-ray diffraction for crystalline silica (HSE, 1988). It was found that as control measures are progressively introduced overall exposure fluctuates more widely from work cycle to work cycle. VEM was able to explain these fluctuations by the relative contributions of five distinct phases to the work cycle: splitting, stacking, waste disposal, housekeeping and conveyor work.

Peak exposures. Knowledge of short term, task specific sources of exposure is becoming more important because, for many industries, these are the major sources of exposure over the whole 8 h shift period (Preller *et al*., 2004). For solvents in particular, workers can be exposed to very high peak or short-term exposures yet and still be below the relevant exposure limit (Stear, 2002). There is concern that high short-term exposures could also result in chronic ill health. VEM (using PIDs calibrated with isobutene and using the buta-1,3-diene response factor) was used to monitor exposure of tanker personnel during coupling and uncoupling hoses (Stear, 2001). Peak levels (averaged over a few seconds) of 14 and 68 p.p.m. for coupling two tankers were found, and 174 and 984 p.p.m. for uncoupling, while the 8 h TWAs were 0.2 and 1.8 p.p.m. (UK 8 h MEL for buta-1,3-diene is 10 p.p.m.).

Risk communication

Risk communication is a general expression describing education and training tools for getting the message across to key players about hazards, risks and controls. VEM is well suited as a workplace risk communication tool as it is a high visual technique. The ability to graphically show the workers themselves, health and safety practitioners, management, specialist occupational hygienists and policy makers how exposure occurs and how it can be controlled has been one of the most important uses of VEM since its inception. Over the years, the medium has changed (from video to CD to web-based and DVD) but the following examples illustrate the more prominent uses of VEM output for training and educational material.

Production of training films makes it possible to spread the knowledge gained at one workplace to a larger circle. The results of a successful (or unsuccessful) measure is worth knowing for it can be of use at other workplaces with the same or similar problems. VEM was used as part of a professional educational video providing guidance on good practice and advice on practical control measures for the UK foundry industry relating to exposure to dust and fumes (Castings Technology International, 1998). It is possible, however, for the VEM users themselves, who are typically not professional video makers, to produce video with the help of relatively inexpensive editing software. Such a video will not have the picture and sound quality of a professional one, but the message can still be communicated effectively. A number of such videos have been produced by NIWL. They illustrate examples from control of exposure to air contaminants, welding, GRP-production, wood dust and pollution control measures at work. The training films have been used in different target groups and by different disseminators, e.g. the labour inspectorate, branch organizations, trade unions, employers' associations and teachers in high school or other study groups (Andersson and Rosén, 1990; Rosén and Andersson, 1990).

The rapid development in media technology has made it possible to store and distribute large amounts of data inexpensively. This, in combination with new study techniques, provided the opportunity to produce training material with texts supported by video illustrations. The document ('e-report') contains VEM video illustrations and pictures to clarify and visualize the message in the text. The illustrations are easily accessible by hyperlinks connected to clickable words in the text. Links allow the content to be approached from different points of view. This is a more effective way to disseminate information or give an expert opinion to a workplace than the traditional method based on written text. CD-ROMs on different topics and for different study groups have been produced with this technique (Andersson *et al.*, 2002, 2003; Kisting, 2003).

Generally, the circumstances for generating occupational hygiene reports at the workplace have changed dramatically. Digital pictures and recordings offer means for gathering 10–100 times more data than written methods. Of course, the data have to be interpreted to be useful, nevertheless these techniques can help with this process. For example, workroom dimensions and shapes, exhausts, cooling and controls and lighting can easily be documented in a single picture during occupational surveys or measurements. With no extra effort 20–50 photos can be taken in a workday. Detailed information about the work, chemicals, ventilation and preventive measures etc. can be studied later and can be combined with written reports using digital pictures, videos, VEM videos and CAD drawings. In addition, the structure of an electronic report is flexible. In addition to the report, a variety of presentations for different groups of personnel is available. This is one of the cornerstones of risk communication and the participatory process.

Worker participation and motivation

When a new development needs be to initiated, it is important to motivate and involve all personnel at the workplace. Seeing oneself or a colleague on video along with information on how exposure varies with one's working methods etc. is a step in the right direction, Fig. 5 illustrates this effect. This makes it possible to use the viewer's curiosity and knowledge in a positive way. Presentation is made even easier by the fact that the results can be viewed as the measurements are being made. It has been shown in many examples that the use of VEM is the starting point for fruitful discussions among workers and staff and which later results in an improved work environment (Frostling, 2002).

WISP (workplace improvement strategy by PIMEX). Visualization helps to understand the details of exposure and innovate preventive measures. Visual situations are understood by both technical experts

Fig. 5. Participation and motivation using VEM at a welding workplace.

and employees almost independently of their cultural background. So all the know-how can be utilized, commitment increased and misunderstanding eliminated. This provides a good basis for improving conditions at the workplace using a participatory approach.

A concept for a participatory process (WISP) has been initially developed and tested in nine companies in a European joint project with Austrian, Finnish and Swedish collaborators (Heinonen and Säämänen, 1999; Rosén, 1999; Andersson *et al*., 2000; Säämänen *et al*., 2000). The process has been further developed in a national project (Säämänen *et al*., 2002). The main aim of the process in the company was to (i) gather company knowledge (ii) obtain occupational hygiene knowledge, and (iii) utilize visualization methods, e.g. VEM, to enhance knowledge and emphasize the relationship between work tasks and exposure. The process facilitates the initiation of an internal workplace improvement project in the company.

A development group, formed in the company, uses the visualization methods to identify reasons for high exposure and also seeks better way and means of controlling and evaluating the efficiency of different control measures. The visualization methods deployed have been the VEM-method, principally, smoke visualization of the air flow, the dust lamp for source identification and various methods for graphical presentation of measured data. The process applies a general problem-solving model (or development cycle) consisting of the following phases:

1. Visualization methods are used in studies dealing with the variation in exposure, its causes, the effect of simple changes etc. When the causality between process events or work tasks and the quality of production environment is well known, it is relatively easy to derive ideas for improvements.
2. The results are analysed in more detail. Task analysis methods, such as detailed exposure analysis (Andersson and Rosén, 1995) are used to identify the tasks which contribute most to the exposure.
3. The results and exposure videos are presented to the development group as the basis for an idea generation meeting. Several kinds of working methods, e.g. brainstorming, can be used in this phase. A clear distinction must be made between providing a solution and the kind of solution chosen for that purpose. The results of the discussions will form the basis for decisions regarding different control measures, evaluation and follow-up of the results.
4. The feasibilities of the ideas are compared and suitable solutions are chosen for implementation.
5. The progress of the implementation is followed. Possible obstacles in the implementation are discussed and solved in follow-up meetings. If the solution for the problem is obvious, then the process can go directly to the implementation phase.
6. After implementation, the success of the control measures are evaluated and the exposure-monitoring program is continued.

Research

As a tool for occupational hygiene research, VEM provides many opportunities. The wealth of information that is found in a picture, combined with the monitoring data from one, two or possibly more instruments, can provide the basis for research on such topics as the connection between production parameters and exposure. The technique has also been used to assess the effects of various ventilation systems (Rosén and Andersson, 1990; Andersson *et al*., 1991, 1993; Andersson and Rosén, 1994). A worker who performed spray lamination and post-spray rolling of bathtubs in a reinforced polyester plastic factory was studied by VEM. The aim was to evaluate the effect of a temporarily installed suspended ceiling with four air inlet devices. The ventilation system was newly developed and it was important to learn about its effectiveness in real work conditions. With VEM, it was possible to follow the worker bending down often and operating near the wet surface; these activities increased his exposure when no protective input air was supplied. The field study, however, confirmed the protective effect of the investigated control method (Andersson *et al*., 1991).

DISCUSSION

Exposure visualization with video (VEM) is now an established method used by practitioners and research teams in different countries. It is, however, not as widely used as we think it should be even though the method's advantages for different control and training purposes in occupational hygiene have, we feel, been amply demonstrated.

The experiences from the applications described in this review illustrate how exposure visualization with video can act as a catalyst, initiating a change process in the workplace, which involves all necessary players: managers, occupational hygiene experts and, most importantly, the exposed worker. This is possible because the persons involved can see the same thing, immediately at the workplace or later, after more detailed analysis of the recorded material. It allows the occupational hygienists to base their analysis and potential solutions to problems from the starting point of the workplace personnel's own expertise. It offers a greater interactive approach to problem-solving than the expert going out to a workplace, analysing the problem then writing a report for the company on the proposed solution. The participative approach lays the foundation stone for improved motivation and commitment for occupational health control measures in the workplace.

There are too many examples of excellent occupational hygiene work aimed at reducing hazardous exposure which have failed. This is not because anything was wrong in technical terms but because the solution was not established firmly and accepted by the users. The users of VEM methods can provide evidence of the typical course of events in different workplaces. After a few minutes of working with the method and when the results are played back, a discussion usually starts about the possible reasons for an exposure peak and what can be done to avoid it. Questions invariably follow, e.g. 'What happens if we do it like this instead?' and 'May I try this work task to see how it looks?' Thus, the commitment for continued participation is established.

Many cases exist where there are good technical prerequisites for hazard control in the workplace but, unfortunately, this has not always led to improvements in working conditions because of a lack of understanding of the technical solutions. It is, for example, easy to find welding stations equipped with excellent and expensive local exhausts which are either partially or completely ineffective. In such cases is it very often easy to reduce the welders' exposure to fumes by 90% simply by providing the welder with the opportunity to see and understand the utility of the exhaust (Rosén, 1999). This is a consequence of the participative approach and the fact that many control measures are used ineffectively is because of the lack of (a) knowledge of how best they should be utilized and (b) the motivation to use such knowledge. Similar results have been demonstrated when the worker is close to the emission source, e.g. spray painting in a booth (Rosén and Andersson, 1989) or manual handling of dusty material (Gressel *et al*., 1987).

The immediacy of the effect of VEM is not its only advantage. If the exposure visualization work is completed at the work site without further development, the immediate participants will have learnt a lot but the probability that this knowledge will actually be applied is limited. The outcome is clearly improved by further analysis of the material and by ensuring that the feedback of the results enter a strategic, solution-seeking process. The potential for further use as part of a more general training material is obvious and many such training videos or training CD-ROMs have been produced at NIWL.

The different solutions for VEM presented here are all available for use by occupational hygienists. The interested hygienist has different options: buy an exposure visualization service (e.g. via a consultancy), or purchase/hire commercially available equipment and learn how to use available software. There is obviously still scope for further technical enhancement of VEM techniques. How these developments proceed is, however, dependent on potential users adding more resources. The threshold for potential users to invest in VEM is comparatively high, depending on the cost, practical availability and arguments in favour of marketing the service. The development and demonstration of applications must, therefore, take a higher priority over the need for easily identifiable technical developments.

The total cost of utilizing VEM comprises the costs of the expert's time and equipment. The use of VEM takes more time than 'usual' occupational hygiene measurements, but often these measurements have already been done and yet the problem remains unsolved. If the detailed task analysis is performed using conventional measurement methods, then the time required may be of the same order. The cost of hiring the service or purchasing one's own equipment must be balanced against the method's potential. If, for example, an engineering workshop decides to reduce the welders' exposure to welding fumes, the investment required may be thousands of Euros. But simply buying technical control equipment may have only a limited effect. If, however, the investment also extends to a change process supported by exposure visualization, the effect will be clearly noticeable with the workers' involvement. Therefore discussions of the benefit of such an investment should include the cost of the consequences of the workers' exposure to the hazard.

VEM should not be seen as an alternative method for assessment of compliance with occupational exposure limits. The method is essentially a tool for improvement of control strategies. This implies that typical quality demands on exposure assessment methods are not completely applicable to the monitoring instruments used for VEM. It may not be so important to calibrate, e.g., for a certain solvent in a mixture of solvents or to know very accurately the concentration of chromium (VI) in the welding fume. It is invariably the case that VEM methods are employed when it is already known that control measures are needed, possibly by previously using more accurate monitoring methods. What is now required is a method that can demonstrate clearly the link between the workplace situation and exposure. We can, in most cases, be very sure that if we reduce the total amount of solvent in the painter's breathing zone, as measured with, e.g. a PID or the welder's exposure to smoke measured with a light scattering instrument, we have also reduced the exposure to the critical agents. The need for calibration, in order to compare with the occupational limit values for a particular agent, is therefore not so great. It is, however, important that the reading from the real-time monitor is stable over the period of measurement. Specific analytical methods for compliance testing may be used to verify the results afterwards.

The applications of VEM, described above, do not cover the whole area of the occupational hygienist's requirement for control of chemical and physical risks. The first and obvious limitation is that the agent of interest must be measurable with available real-time monitoring instruments. It must be possible to sample at the appropriate point, normally in the breathing zone, and the instrument must respond fast enough. Another limitation is that there must be some link between what can be seen in the video and the variation in exposure. For example, welders' exposure to fumes is very much dependent on how they act, how any exhaust is deployed etc. However, exposure to hydrogen sulphide in a pulp mill, for example, is possibly more dependent on the background concentration, which may arise from many diffuse emissions sources (leaks) in the process. Consequently, the workers' behaviour does not affect their exposure. The closer the link between the source of the agent and the exposed person, the more useful VEM can be.

As for the future of VEM, developments, both in the technology and the ways to utilize it as a tool for occupational hygiene, can be foreseen. Developments in information and communications technology, especially the ability to process video and real-time monitor data easily, conveniently and inexpensively will, hopefully, help to increase the use of VEM. New wireless networking or other short-range radio technologies are becoming more common in electronics which will help to transfer data between the equipments used in VEM. Also, the trend towards miniaturized and lower cost real-time monitors, which could easily have integral low cost video cameras, will be a contributing factor. Integration with mobile technology (phones, PDAs, etc.) offers an exciting possibility to make it more widespread and acceptable. This should facilitate VEM's wider use by both the companies themselves (usually larger establishments) or consultants (usually employed by SMEs). The ready availability of 'open-source' software for the PIMEX-PC system, for example, could lead to Linux type continuous development.

While these technical developments will help in the uptake of VEM, a significant amount of resource is necessary for training in the use of VEM equipment and the consultative process. Dedicated VEM monitors, as mentioned above, would help to reduce the complexity of operating electronic equipment. The use of good VEM case studies to illustrate the power of the technique with, possibly, cost-benefit analysis can convince the participating company of the value of investing effort in the process. The technique can play an important role in increasing worker and public awareness of risks associated with chemical, biological and physical agents.

New computer graphics with web-based design (e.g. Macromedia Flash) and DVD authoring software packages will enable eye-catching presentations of guidance to be generated based on VEM data. These presentations would employ, in addition to normal video footage, animation and interactive sessions to emphasize key points and get the message across on good work practice and the use and effectiveness of controls.

Other applications that could extend the technique include: (i) visualization of tracer gas methods (visible and infrared wavelengths, smoke and chemical tracer gases); (ii) self-training applications with small wearable systems; (iii) improvement of well-being, comfort and productivity at work; (iv) noise visualization (e.g. www.acoustic-camera.com); (v) biosensors; biological monitoring. However, in practice, the skills and knowledge of an occupational hygienist are the main issues.

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