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Perspective

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Retrospective analysis of the exposure assessment following chemical incidents

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Abstract

This article proposes an integrated exposure assessment approach to improve the identification of vulnerable groups by using spatial and temporal data during chemical incidents. A perspective view was proposed in the integrated approach. The exposure assessment was based on continuous and direct environmental monitoring. The exposure assessment was complemented by human biomonitoring measurements. A tired approach of environmental hazard, exposure level, and exposure factors was used to identify vulnerable groups. Each step assessed the level of exposure, delineated areas, and exposures were identified. This paper shows that the collection of direct measurements in the days following chemical incidents helps to monitor the evolution of the exposure. By performing continuous measurements in time and space, vulnerable groups within the general population can be identified in a timely manner. In conclusion, dynamic measurements in exposure assessment help to protect vulnerable groups with adapted public health recommendations. This integrated exposure assessment is adapted to different event contexts, such as industrial accidents, natural disasters or routine environmental monitoring, to determine soil contamination in order to prevent health impacts.

Perspective

During and after incidents, professionals collect vast amounts of data to identify at-risk groups and take protective measures. Decisions need to be made within a short timeframe to rapidly implement protective measures. This includes preparing an evacuation action plan and taking environmental measurements [1,2]. The risk assessment process consists of four main steps: 1) hazard identification, 2) dose-response assessment, 3) exposure assessment, and 4) risk characterization [3,4]. According to the World Health Organization (WHO), risk assessment methodologies enable policy-makers to make appropriate and informed decisions. The risk assessment process also guides how to conduct human health risk assessments and follows a series of sequential steps in which the probability that a particular chemical causes an unfavourable/adverse outcome in the general and susceptible populations is assessed [4,5]. Both environmental and health risk assessments aim to understand and reduce the health impacts of chemical exposure [5]. While exposure assessment must be considered as an emergency response in the context of an incident, further research is still needed to adapt its use in post-disaster environmental management [6,7].

Integrated environmental data and human biomonitoring (HBM) provide a high level of confidence in the exposure assessment and characterization to support decision-making [8]. Human biomonitoring is used to determine the internal exposure of humans. The latter represents the chemical body burden of chemicals and/or metabolites [9]. These biomarkers in the human body help to characterize individual exposure and vulnerability, and to understand the mechanisms of action of chemicals. The paper aims to highlight the added value of an integrated exposure assessment during chemical incidents. Two operational objectives were identified: 1) to define parameters that modulate environmental and human health exposures during a chemical incident, and 2) to demonstrate how an integrated exposure assessment can improve the assessment of chemical spills and, using a geocoding system, help to identify the vulnerable groups exposed during chemical incidents. From the present perspective view, data from environmental media and HBM studies following a major incident were combined to improve the exposure assessment process. We implemented an integrated approach based on the risk assessment as defined by the WHO (2021) and the HBM campaign to optimize the assessment of a chemical exposure that occurred during an incident (Table 1). Each step was considered using a tiered approach, taking into account the level of complexity in terms of data availability [10,11].

According to these authors, three levels of detail were identified: 1) information on spatial and temporal data to characterize the risk of exposure is missing; 2) information on spatial and temporal data to describe the concentration distribution and exposure of the population is available and accurate; 3) information related to spatial and temporal data by integrating exposure parameters such as distance from the event, time and duration of exposure, and parameters of vulnerable groups is complete [10,11]. Detailed mapping has been proposed to visualize exposure pathways in the environment. Furthermore, a high level of information allows the description of health impacts by considering an exposure index where process emissions, environmental conditions, and personal behaviour have been added [8,12]. Therefore, human health risk assessment must start with clear objectives based on the problem and the context of the situation. Exposure incidents are analyzed in two successive phases, the acute phase following the chemical incident. In this phase, environmental measures and incident status are assessed depending on the hazard. The post-acute phase is concerned with the HBM and health status assessment. To improve the exposure assessment process and to facilitate the identification of vulnerable groups exposed to chemical incidents, Figure 1 illustrates parameters that modulate environmental and human health exposure during a chemical incident.

Hazard identification: environmental monitoring and data collection: for the chemical in question, information must be screened against updated and accurate databases (e.g. safety data sheets): the incident phase involves defining tasks based on the initial information collection and control measures related to: international chemical safety cards; chemical properties such as the vapor cloud explosion (VCE) or the boiling liquid expanding vapor explosion (BLEVE). When a chemical triggers an explosion, a highly toxic gas is produced. Based on the BLEVE aspects, the safety perimeter is usually established by the emergency rescue team; route of human exposure (for example, for a BLEVE priority chemical, the route of exposure is mainly by inhalation, water-soluble gases, etc.); environmental pathways (for BLEVE chemicals, the sources of exposure are air and water); pollutants with short-term impacts [respiratory irritants and asphyxiants] or long-term impacts. The post-incident phase with HBM campaigns includes biomarkers of exposure in the human body for HBM campaigns, and guidance values for exposure rates in the environment and from HBM values from epidemiological data.

Risk characterization: based on the main route of exposure, reference values (available from the international environment and health agencies) must be selected to determine the sampling methods (air, water, soil). Routes of exposure that are specific and known to cause an acute effect on human health must be considered to predict the distribution of the chemicals in the environment. Air quality for human health is first used to interpret the measured concentration of the chemical. To estimate the risk that is expected to affect human health, the identified limit values have been associated with the maximum contaminant level, which is the highest level measured after the chemical incident.

Exposure descriptor: delineation of areas and data collection: environmental monitoring was carried out concerning the BLEVE property, which defines the area delineation from the chemical incident site to which residents must be evacuated. Direct measurements enabled the identification of maximum levels, which allowed accurate assessment of exposure risk and identification of hotspots. The results of direct measurements provide accurate data on the hazard levels, which constitute a preliminary interpretation of the exposure.

Dynamic measurements to assess spatial trends: where measurements are not possible because of the areas, volumes, and large geographical areas that affect the quantification process, scenarios or exposure models can be used as an alternative. These models or exposure reconstruction scenarios add value to the direct measurements but should not replace accurate and real emission rates. Direct measurements of the environmental media such as air, water, and soil are important factors in determining exposure levels and estimating the potential human health impacts. The emission rates must be determined as soon as possible. In the case of chemical incidents, air sampling must provide rapid information on the chemicals released into the environment. This essential step involves the use of a pump and colorimetric detector tubes, that deliver instantaneous measurements. Once the main chemicals have been identified, their concentration can be quantified and performed by using, for example, a photoionization detector. The duration of the environmental measurements must be dynamic and reflect the environmental persistence properties of the chemical, i.e. its half-life in all environmental media. It is important to consider that chemicals may be transported through several different pathways. Dispersion represents downwind movement and crosswind and vertical spread [13]. The theoretical dispersion model indicates the first area that needs to be evacuated from the chemical spill. To have a real indication of the contamination and to identify vulnerable groups around the chemical incident, this dispersion model needs to be completed with direct measurements from environmental sampling. The geographical extent of the contamination can be determined by analyzing chemical properties, such as the half-life of the molecules in the environmental media. These data are used to estimate the duration of the measurements to be conducted in the main media responsible for the contamination and the dispersion affecting exposure. This makes it possible to reconstruct the exposure a posteriori, if necessary.

Spatiotemporal trends: following an incident involving a chemical with BLEVE properties, air, and water have been identified as the primary pathways for environmental contamination. By considering the half-life of the molecules as a function of the medium, it is possible to detect the presence of the chemical far away from the incident site and outside the evacuation zone. The analysis showed that the chemical spread in the environment through the waterways within weeks. In addition, natural events such as heavy rainfall and flooding, or a poor/deficient sewerage system, can lead to flooding of the main sewers [14]. This can also happen after large volumes of water have been used to extinguish the burning tank, potentially leading to an uncontrolled release of the chemical into the environment, over time and space [15]. To anticipate the release of chemical contamination and this risk, it may be helpful to carry out a comprehensive environmental analysis of soil, water, and air to vegetation, building materials, and debris, and to consider several scenarios using Monte Carlo analysis [2]. The sampling protocol should be regularly adapted to reflect the evolving situation and the meteorological conditions so that the locations to be monitored and the number of air samples to be taken are not particularly similar throughout the study period. This aspect has a strong influence on the trends in chemical concentrations and the resulting interpretation.

Human biomonitoring and data collection: human biomonitoring (HBM) is a post-disaster assessment aimed at better understanding chemical exposure following an incident and optimising health monitoring of the exposed population. The delay to conduct the HBM may vary and several parameters need to be considered. Human biomonitoring (HBM) can be carried out if the local context and ethical aspects allow it. The aim is to investigate the potential health effects of the contamination and support decision-making during the monitoring process. This is an important step in establishing the questionnaire aimed at identifying exposure determinants. In conjunction with this approach, the physicochemical properties of the substance must be determined to select the biological matrix. Toxicokinetic, which refers to the absorption, distribution, metabolism, and excretion of the substance in an organism, must be considered. The bioavailability and solubility of the chemical must also be determined. For example, volatile compounds will be rapidly eliminated from the body by exhalation, hydrophilic substances will remain dissolved in the urine, and lipophilic compounds will not be readily eliminated from the body.

The health consequences of chemical exposure can range from respiratory tract irritation and fatigue to nausea, vomiting, convulsions, coma, and even death. It is therefore important to monitor human biomarkers to detect early signs of exposure and ensure prompt treatment. Chemicals can have acute effects that can be life-threatening and some are possible human carcinogens. Biological matrices provide an aggregated measure of the level of exposure to chemicals from all sources: at work, at home, and from other environments [16]. The choice of the biological matrix depends on several parameters such as the half-life of the chemical in the biological matrix and its bioaccumulation properties, the chemical being analyzed, and the existence of a biological limit value. The most used biological matrices after disasters have been urine, blood, hair, or exhaled human breath. Hair length can provide a history of exposure and the possible contribution of a particular chemical during the incident. Exhaled breath is also used to assess environmental exposure, particularly for inorganic and organic compounds in the gas phase and several hundred volatile organic compounds [17]. Both matrices are non-invasive methods, which may increase patient compliance and may be best suited for vulnerable individuals and young children (depending on the condition of the hair).

In addition, the interpretation of HBM results is not straightforward due to the differences in toxicokinetics and toxicodynamics between animals and humans [9]. Accurate and sensitive analytical methods are essential to provide HBM data. A questionnaire can help to investigate the health effects of the chemical and to identify other sources of exposure, thus allowing to distinguish the role of the event and its influence on the biomarker concentration [18,19]. Mid-term follow-up is recommended to collect data on the biomarker trends and to assess the impact of the chemical incident on the health of the exposed population [20]. Human biomonitoring provides an opportunity for reliable exposure reconstruction following accidental exposure to chemicals [21]. The spread of a chemical in the environment within weeks highlights the need to adapt health risk assessment and communication during incidents.

Integrated data analysis: the proposed risk assessment index is based on exposure factors [8] and includes: area delineation of the incident provides an estimate of the hazard in the environmental media from the maximum value of the chemical air concentration and the second identified exposure pathway; reference and limit values for exposure analysis and risk characterization; general concentration is measured from outdoors and, if necessary, indoors and must be interpreted by using the self-administered questionnaire; duration and frequency of exposure, assessed with the dynamic measurements from the site of the chemical incident to the hotspot areas identified as posing a risk to human health, and concentration of the chemical contaminant in the human body was assessed and completed with a self-administered questionnaire.

Mapping the environmental concentration of the chemical in question and the HBM results, by using geographic information systems, provides an adequate indication of the distribution of the contaminant. The effectiveness of exposure assessment is enhanced by geospatial analysis, which shows that areas with high levels of biomarkers [a metabolite of the chemical in question] correspond to those with high environmental concentrations of the same chemical. This process therefore helps to confirm or refute the contamination resulting from the incident, and to identify other additional sources of exposure contributing to elevated measured concentrations. This approach categorizes the area of chemical contamination into different zones based on the superposition of layer data (environmental data and individual concentration) and can be used as a decision-making tool during emergency management. It can also be used to determine land contamination in other contexts where health effects and environmental pollution can be prevented (for example, industrial accidents, routine environmental monitoring, etc.). It can also be used to identify the release of harmful substances or contamination from industrial sites, and known contaminated areas into the surrounding environment which can lead to incidents such as explosions, fires, and chemical spills. Systematic data collection is required to support a structural characterization and management of exposure risks [22]. Consequently, continuous environmental monitoring should be carried out continuously during incidents [8,23]. The integration of environmental and health impact assessments adds value to the exposure assessment of major chemical incidents (Table 2).

Conclusion

Although many exposure assessment protocols have been developed, the study results indicate that only a few approaches have been identified for use during incidents. The integration of environmental and health data during a chemical incident is challenging and approaches need to be contextualized depending on the incident and the hazard that is identified. The proposed exposure index in an integrated approach could be used in a case study, or during a disaster scenario exercise. However, this implementation of exposure assessment processes in practice could present some limitations. Public health objectives and the availability of resources are determinants for achieving a detailed exposure assessment. The integration of the exposure approach involves continuous monitoring of the intensity, frequency, and duration of exposure. Continuous measurements allow the assessment of the evolving risk to the population that may be exposed to significant levels of the chemical for prolonged periods of time (as estimated by the half-life estimate in the literature), and to adapt public health decision-making. In the future, this concentration mapping could be used to prevent environmental contamination and even be used in the event of a natural environmental disaster. The identification of exposure determinants, such as potential sources of contamination and pathways of human exposure during a chemical incident, is achieved by analyzing both environmental monitoring and HBM. By adding a high level of detail to the assessment process, it allows for the identification of vulnerable groups that may be exposed. Human biomonitoring is a complementary tool to environmental monitoring in exposure assessment during a chemical incident. Spatial and temporal data integration provides efficient results for exposure assessment and risk characterization.

Competing interests

The authors declare no competing interests.

Authors' contributions

All the authors have read and agreed to the final manuscript.

Tables

Table 1: information and level of detail to integrate into a risk assessment (WHO, 2021) and human biomonitoring (HBM) campaign

Table 2: added value of an integrated approach to human health risk assessment during a chemical incident

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Table 1: information and level of detail to integrate into a risk assessment (WHO, 2021) and HBM campaign

Steps	Description	Information and level of detail
Problem formulation	Scope of the problem and issues; analyse the degree of uncertainties	Definition of the question and objectives; inventory of the knowledge; estimation of the time and resources required; study design; analysis plan
Hazard identification	Identifies the type and nature of adverse health effects	Human studies; animal-based toxicology studies Structure-activity studies; predictive technologies
	Biomarkers in human body	Biological matrices; levels of concentration; biomarkers of exposure and effects; analytical methods
Hazard characterisation	Qualitative or quantitative description of inherent properties of an agent having the potential to cause adverse health effects	Selection of critical data sets; modes/mechanisms of action; kinetic and dynamic variabilities; dose/exposure-response for critical effects
Exposure assessment	Environmental monitoring: chemical incident status evaluation of the exposure situation of the (sub) population previously identified	Characteristics of the exposed population; sources; magnitude level of concentration in environment medias; frequency; duration; route; area contamination
	Human biomonitoring: self-questionnaire; symptoms - medical history	Individual exposure; biomarkers of exposure; vulnerable parameters (environmental factors and personal behaviours) Contamination sources; identification Determine the sources from the incident
Risk characterisation	Risk level estimation; human health risk; advice for decision-making	Recommendations or quantitative guidance or risk estimates; nature and severity of effects; probability of effects; health-based guidance; population of concern; pncertainties

HBM: human biomonitoring

Table 2: added value of an integrated approach to human health risk assessment during a chemical incident	
Delineation and risk characterisation of chemical exposure during an incident	
Media identification and chemical behaviours in environmental media. Half-life is the media estimation for the chemical involved in the incident.	Accurate and adjusted direct measurements in time and space from the chemical incident. Chemical pathways properties to control environmental contamination.
Identification of hotspots with significant "risk" and "immediate hazard" levels for human health for groups of individuals. Those hotspots may differ from rescue areas identified from the delineation process to evacuate residents.	
Analysed distribution patterns of chemical contamination in the environment throughout measurement. Results may show the presence of an uncontrolled release of the chemical in the air.	More people mobilised to collect data. Knowledge of the integrated exposure assessment is incomplete for the entire rescue team.
Patterns of chemical concentration provide information on the persistence of this molecule in the environment and help to identify the vector of contamination and the source of exposition.	
Vulnerable groups	
HBM matrices golden standards. Estimation of the bioavailability and bioaccessibility (matrices correlated and adapted to the chemical metabolites in the body).	Exposure analysis process. Human health risk estimation.
Half-life in biological matrices estimation for the chemical involved in the incident.	
Vulnerable groups were identified following the exposure determinants.	Individual factors (children, pregnant women, elderly people, etc.) Individual activities (rescue team, health workers).
Identification of vulnerable sub-populations through outdoor and indoor exposure measurements.	
Environmental and human biomonitoring data	
Exposure correlation between environmental monitoring and biomarker monitoring in time and space.	Data analysis for geospatial patterns of exposure.
Risk characterisation	
More detailed characterisation of the risk.	Uncertainties related to the exposure factors during the assessment process.
Monitoring campaigns provide patterns of exposure and make it possible to adapt protective measures.	Public health recommendations.