MONITOR AND SENSORS 2.0 FOR EXPOSURE ASSESSMENT TO AIRBORNE POLLUTANTS

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ABSTRACT

In recent years, the issue of exposure assessment to airborne pollutants has become increasingly popular, both in the occupational and environmental fields. The increasingly stringent national and international air quality standards and exposure limit values both for indoor environments and occupational exposure limit values have been developed with the aim of protecting the health of the general population and workers. On the other hand, this requires a considerable and continuous development of the technologies used to monitor the concentrations of the pollutants to ensure the reliability of the exposure assessment studies. In this regard, one of the most interesting aspects is certainly the development of "new generation" instrumentation for monitoring airborne pollutants ("Next Generation Monitors and Sensors" – NGMS). The main purpose of this work is to analyze the state of the art regarding the afore-mentioned instrumentation, to be able to investigate any practical applications within exposure assessment studies. In this regard, a systematic review of the scientific literature was carried out using three different databases (Scopus, PubMed and Web of Knowledge) and the results were analyzed in terms of the objectives set out above. What emerged is the fact that the use of NGMSs is increasingly growing within the scientific community for exposure assessment studies applied to the occupational and environmental context. The investigated studies have emphasized that NGMSs cannot be considered, in terms of the reliability of the results, to be equal to the reference measurement tools and techniques (i.e., those defined in recognized methods used for regulatory purposes), but they can certainly be integrated into the internal exposure assessment studies to improve their spatial-temporal resolution. These tools have the potential to be easily adapted to different types of studies, are characterized by a small size, which allows them to be worn comfortably without affecting the normal activities of workers or citizens, and by a relatively low cost. Despite this, there is certainly a gap with respect to the reference instrumentation, regarding the measurement performance and quality of the data provided; the objective to be set, however, is not to replace the traditional instrumentation with NGMSs but to integrate and combine the two typologies of instruments to benefit from the strengths of both, therefore, the desirable future developments in this sense has been discussed in this work.

INTRODUCTION

First, we want to explain the meaning of the most used word in this manuscript, in order to avoid any misunderstanding that will occur between the authors and the readers of this work. By "sensor" we mean a component that is part of an instrument which, through physicochemical properties, can translate an electrical signal into environmental concentrations of airborne pollutants. By "monitor" we mean the entire monitoring system, equipped with one or more sensors and the whole components (i.e., batteries, case, display, etc.) which allow it to perform properly. As already said, the aim of this work is to characterize, investigate and suggest some future developments regarding the so-called "next Generation Monitors and Sensors" (NGMSs), or rather the most recent sensors and monitors characterized by the miniaturization and/or by the low cost and/or by the propensity to be worn easily. Regarding the definition of "*miniaturized monitors"* (MMs) we refer to a previous study [8] which defined as MMs all the devices that have the highest dimension lower than 20cm. This definition can be adopted arbitrarily because in literature doesn't exist a universal one; more generally it is possible to refer to MM as all the ones which have dimensions smaller than the traditionally used instrumentation. A category of that last ones is the one of "*wearable monitors"* (WMs) which are identified as all the monitors able to be worn by the subjects in order to obtain *real-time* data aiming the evaluation of personal exposure. Lastly, when we used the terminology "*Low-Cost monitors*" we refer to all that monitors which cost is about the order of magnitude of hundreds dollars or euros.

The interest regarding the environmental and occupational exposure assessment to chemical airborne pollutants can be related to the fact that these are directly associated with a lot of adverse effects, acute and chronic both, on human health, which depends on which are the considered pollutants. The most of the population, both in the occupational and environmental fields, is continuously exposed to airborne pollutants concentrations which frequently exceeds the limits values imposed by the World Health Organization (WHO). So, it is fundamental to evaluate the human

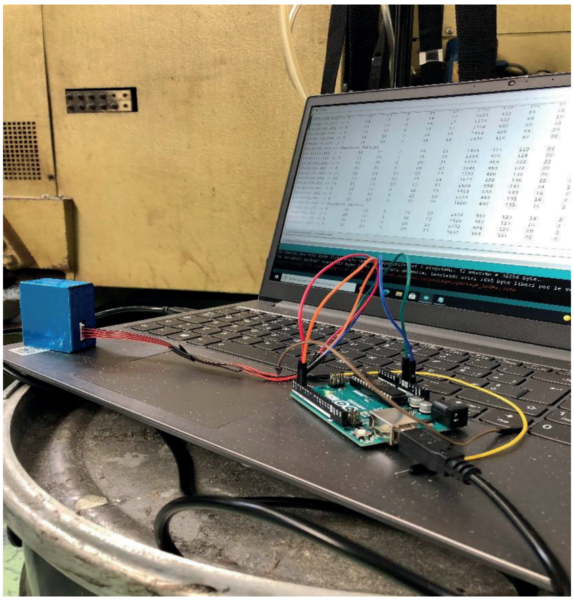

Fig. 1 - *PMS5003 sensor plugged into Arduino Uno during the preliminary study.*

exposure to airborne pollutants, aiming to identify the emissions and manage the related risks. In order to obtain a proper evaluation of the impacts on human health, the airborne pollutants exposure, should be continuously monitored (24/7: 24 hours per day, 7 days per week), following the exposome concept.
Traditionally used instrumentation for the monitoring of pollution levels can provide precise and accurate data but can't characterize the single subject's exposure in terms of spatio-temporal resolution, a fundamental aspect to obtain exposure data more reliable as possible and to approach the exposome research field. Due to these facts the development of monitors and sensors which allows measuring personal exposure in a better way it is considered essential. In the last years was been reached important goals concerning the development of innovative monitors and sensors, more and more miniaturized, *user-friendly, wireless* and *smart* contributing, in this way, in the spreading of the exposome concept in exposure assessment studies. An emerging technology that deserves to be mentioned is the "*Wireless Sensor Network"* (WSN) one. This technology consists of a sensors network that is able to communicate with each other and acquire information simultaneously with high spatio-temporal resolution. Given these premises, it can be argued that all these technologies can support occupational exposure assessment studies to airborne pollutants, which must fall within the context of worker health protection in order to develop preventive policies and standards. All these aspects are receiving more and more attention also in the context of occupational risk assessment, following the emerging concepts of "*total worker health"* and "*occupational exposome*", which have numerous points in common with the issues exposed so far in this discussion, and which could certainly benefit from the introduction and development of new NGMSs that are increasingly more and more performing and reliable. The advancement of practices in conducting exposure monitoring studies must be guided by the specific needs of experts in the sector and not by the adaption of the latter based on the availability of available instrumentation. Due to this reason, starting from previous experiences and a systematic review of the most recent scientific literature, the goal of this contribution is to propose the development of a multi-parametric device for monitoring airborne pollutants. The aim is to make available to the final users, not mandatorily only experts, the most up to date sensors/monitors technologies allowing its usage also in exposure assessment studies both occupational and environmental.

MATERIALS AND METHODS

Thanks to previous monitoring campaigns several criticalities concerning the type of instrumentation traditionally used to acquire airborne pollutant exposure data already emerged. To try to (i) rationalize these criticalities and (ii) identify the most appropriate sensors for the purpose defined in this work, a systematic review of the literature was set up, conducted by inserting a list of keywords in three different databases (i.e., Scopus, ISI Web of Knowledge and PubMed), selecting them from among those related to the assessment of exposure to airborne pollutants, with a look at innovation. More information on the review process can be found in Fanti et al., 2021 but some fundamental aspects will be exposed below. All the papers included in this review process have been analyzed aiming to acquire information regarding sensors used to monitor airborne pollutants concentrations. In particular, if a sensor was assembled within a multi-parameter device it was cataloged as a single sensor. Furthermore, other specifications of interest were also considered such as the use of GPS technology and the presence of sensors capable fo measuring

Pollutants	Sensor	Sensor Technology	Dimension	Cost
NO_2	Alphasense NO2-A43F	EC	20,2x16,5mm	48,00€
O_3	Alphasense OX-A431	EC	20,2x16,5mm	50,00€
CO	Alphasense CO-A4	EC	20,2x16,5mm	50,00€
PM	Plantower pms5003	LS	38x35x12mm	25,39€
Other Parameter				
T–RH	Aosong AM2302 – DHT22	CS–TH	25,1x15,1x7,7mm	7,99€
GC	Adafruit Ultimate GPS chip	GPS	2,55x3,5x0,65mm	55,66€

Tab. 1 - *Pollutants and sensors of interest and other parameters (T-temperature; RH-relative humidity; GC-geographic coordinates) investigated and relative technologies (EC-electrochemical; LS-light scattering; CS-capacitive sensing; TH-thermistor; GPS-global positioning system) that will be integrated into the prototype.*

environmental parameters such as temperature and relative humidity. In 2008, the world health organization indicated the reference values concerning the most common airborne pollutants. In this study we analyzed devices concerning the monitoring of some of the most common airborne pollutants, namely nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), volatile organic compounds (VOC) and air-

Pollutants	Sensor	Sensor technology	Available Paper	Reference
NO_2	Alphasense NO2-A1	EC	1	[47]
	Alphasense NO2-A43F	EC	4	[12,14,20,40]
	Alphasense NO2-B43F	EC	5	[4,25,55,57,69]
	e2V MiCS-2710	MOS	2	[30,42]
	* Sailbri Cooper Inc SCI-608	n.a.	1	[15]
	SGX SensorTech MiCS 2714	MOS	1	[52]
	SGX SensorTech MiCS-4514	MOS	3	[6,28,46]
O_3	Alphasense OX-A431	EC	5	[12,14,20,40,59]
	Alphasense OX-B431	EC	5	[55–57,69,71]
	Nissha FIS SP-61	MOS	1	[55]
	* Sailbri Cooper Inc SCI-608	n.a.	1	[15]
	SGX Sensortech MICS 2614	MOS	3	[4,44,52]
	Winsen MQ-131	MOS	1	[18]
CO	Alphasense CO-A4	EC	2	[14,59]
	Alphasense CO-AF	EC	1	[47]
	Alphasense CO-B41	EC	4	[56,57,69,71]
	e2V MiCS-5525	MOS	1	[61]
	Figaro TGS 2442	MOS	1	[52]
	* Sailbri Cooper Inc SCI-608	n.a.	1	[15]
	SGX SensorTech MiCS-4514	MOS	3	[6,28,46]
	Winsen MQ-7	MOS	1	[18]
VOC	Sensirion SGP30	MOS	1	[19]
	Sensirion SGPC3	MOS	1	[44]
PM	Honeywell HPMA115S0	LS	1	[70]
	Nova Fitness SDS-011	LS	1	[25]
	Plantower PMS3003	LS	3	[6,29,41]
	Plantower pms5003	LS	3	[28,43,58]
	Sharp Electronics GP2Y1010AU0F	LS	3	[1,18,71]
	* TSI OPS3330	LS	1	[48]
$PM_{2.5}$	Alphasense OPC-N2	LS	1	[9]
	Plantower pms3003	LS	4	[5,29,40,51]
	* RTI International MicroPEM	LS	1	[68]
	* Sailbri Cooper Inc SCI-608	LS	1	[15]
	Sharp DN7C3CA006	LS	2	[11,56]
	Shinyei PPD42NS	LS	1	[26]
	Shinyei PPD60PV- T2	LS	2	[7,45]
PM_{10}	* Sailbri Cooper Inc SCI-608	LS	1	[15]
Altri parametri				
T–RH	Adafruit AM2302	CS–TH	1	[71]
	Aosong Electronics DHT22	CS-TH	1	[28]
	CMOS sensor (HTU-21D)	CS-TH	1	[20]
	Cozir AH-1	ND	1	[40]
	* Sailbri Cooper Inc SCI-608	ND	1	[15]
	Sensirion SCD30	CS-SBG	1	[25]
	Sensirion SHT15	CS-SBG	2	[5,29]
	Sensirion SHT31	CS-SBG	1	[41]
	Sensirion SHT75	CS-SBG	1	[59]
	SST sensing CO2S-A	ND	1	[69]
	Texas Instruments HDC1080	CS-TH	1	[6]
GC	G.TOP FGPMMOPA6H	GPS	1	[6]
	Adafruit Ultimate GPS chip	GPS	1	[28]

Tab. 2 - *Pollutants and other parameters (T-temperature; RH-relative humidity; GC-geographic coordinates) investigated, relative NGMS used (when declared), relative technologies (EC-electrochemical; MOS-metal oxide semiconductor; LS-light scattering; CS-capacitive sensing; Th-thermistor; SBG-silicon band gap; n.a.-not available) and the number of papers in which the NGMSs were used. The monitors were marked with "*" to separate them from the sensors. More information are available in Fanti et al., 2021* borne particulate matter (PM) with an aerodynamic diameter lower than 2.5 µm ($PM_{2.5}$) and lower than 10 µm (PM_{10}) (the PM classification aims to include all those NGMSs capable of simultaneously monitoring both aerodynamic fractions investigated). The evaluation of the results emerged from the systematic review process allows identifying the available sensors on the market which most satisfy the needs of this study. The next step has been to start to acquire and assemble the components needed to realize the "hardware side" of the project. Preliminary studies were conducted by combining what can be considered the early stage of the prototype with the instrumentation traditionally used in a context of exposure assessment in an occupational context. The prototype used in this occasion (Figure 1) was composed of a sensor for the acquisition data concerning the airborne concentrations of PM_1, $PM_{2.5}$, PM_{10} (PMS5003, Plantower), a microcontroller board (Arduino Uno by Arduino™) connected to a laptop via USB port to allow systems power and data display through the serial port. In order to acquire the data of interest from the sensor, the program, called *Sketch*, was processed through the Arduino IDE (*Integrated Development Environment*) software and subsequently loaded on the motherboard of the Arduino Uno board.

In the next implementation phases, other sensors of interest will be integrated, detailed in Table 1, for the exposure assessment studies in occupational fields. A sketch will also be developed on an Arduino IDE basis, which will allow to obtain all the data necessary for the purposes of this evaluation. Once the prototype is completed, a monitoring campaign will be launched to evaluate its performance and allow the calibration of the devices.

RESULTS AND DISCUSSION

The scientific production regarding this field seems to constantly grow and this is supported by the fact that 66% of considered publications comes from the last 12 months. The principal results are reported hereafter and in Table 2, more information are reported in detail in Fanti et al., 2021. Regarding gaseous pollutants (NO_2, O_3, CO) the most used sensors are based on electrochemical principles and are the ones produced by Alphasense (www.alphasense.com; July 22th, 2021; Great Notely, Essex, UK). Regarding the sensors used to monitor VOCs concentrations, the most used in the scientific literature are the ones produced by Sensirion. Regarding the monitoring of PM the most common technology on which the devices are based is the light scattering principle and the most used sensors are the ones produced by Plantower.

As already said, also the temperature (T) and the relative humidity (RH) have been investigated in this review because they can considerably influence the sensors abovementioned and so introduce errors on the airborne pollutants' concentrations monitored. Moreover, regarding the GPS sensors, wasn't been found much information except for two papers. This might be due to the fact that these sensors are affected by a high-power supply demand and so is better to acquire the GPS data from smartphones.

A crucial role to increment the interaction between final users and devices is played using mobile apps, which allow to optimize the downloading of data from devices and their upload on cloud platforms in order to make them immediately available for analysis and processing. The most used communication technology was the bluetooth one, which more recently has been further improved in terms of energy consumption, so much so that it has been renamed *Bluetooth Low-Energy technology* (BLE). As argued by Kanjo et al., 2008 the use of mobile apps for data collection can bring several advantages such as (i) the fact that the vast majority of the population is already equipped with a smart-phone, (ii) many types of data can thus be processed, stored and transferred easily and (iii) as previously mentioned, the whole process is more energy efficient because the acquired information is sent directly to the smart-phone without the need for it to be saved also on the device.

From the review of the scientific literature emerged that, to date, the usage of NGMSs is mostly spread in environmental exposure assessment studies which often adopt a *"citizen science"* approach to collect data. In this initial phase, these technologies are used as support tools, in addition to the traditionally used techniques, to evaluate and formulate policies and strategies for the protection of public health. On the other hand, in the occupational field, this instrumentation is not yet systematically used due to the stringent requirements from the point of view of performances (e.g., precision, accuracy, detection limit) that the policies of prevention and human health protection require. Despite this issue, some examples have emerged of how NGMSs can offer great opportunities in the field of safety and human health protection in occupational fields. The NGMSs have been used in studies in the construction sector, with the aim of mitigating the risks deriving from dangerous and physically demanding activities for workers. There are various types of bands, bracelets and watches that can monitor different physical parameters thanks to the integration, within them, of miniaturized sensors. By using these technologies in the occupational field, it is possible to influence the choices of workers, interacting with the environment around them, to reduce any risky situations to which they could be exposed.

The data acquired by the traditional instrumentation are not made available in a short time (even if they might be useful to adopt immediate mitigation risks actions) and are, in most cases, characterized by information regarding one pollutant per device and one single work shift. In the last decades, industrial hygienists, used *Direct Reading Instruments* (DRI) and real-time monitors. The NGMSs can continuously monitor several risks factor simultaneously within the workplace. Moreover, they are smaller, lighter, and power efficient if compared to traditional instrumentation. This fact might be an advantage because thanks to real-time monitoring, the immediate availability of data allows preventing risky situations. In the future, once that all these information will be integrated with geo-positioning system within a workplace, (e.g., production plant, building site, and other occupational workplaces) there will be possible to obtain personal exposure of the single workers while they moving around the workspace. Furthermore, by integrating the data acquired in real-time with machine-learning models, which are able to create a system that autonomously learns to manage the acquired data, it will be possible to exponentially increase the probability of limiting or even preventing the potential risks associated with industrial activity.

Another technology that, thanks to the increasing innovation of microprocessors, is turning out to be an important tool available to health and safety professionals in the workplace is that of *Wireless Sensor Networks* (WSN). WNS means a network of sensors capable of communicating with each other and with a central control system that collects all the information deriving from the various devices. By modeling this information, it will be possible to obtain plant risk maps, and consequently manage the risks arising from each individual workspace, once again with the aim of increasing safety and health protection in the workplaces. At this point it may be necessary to revise the concept of "exposure assessment" because it cannot be taken for granted that it is the most intrinsically suitable to be associated with the use of NGMSs by industrial hygienists. For example, if the NGMSs instead of being used only for monitoring purposes were also exploited to condition the behavior of workers, this would affect the assessment of the real exposure of the subject. In fact, a risk management process based on the acquisition of data in real time would be applied where the activities of workers (and therefore their exposure) vary continuously depending on the information acquired.

Despite the various advantages they introduce, it is important to underline that NGMSs must be accurately evaluated before being deployed, especially with regard to precision and accuracy. This is due to the fact that, if compared to reference instrumentation, NGMSs are nowadays affected by an important gap regarding these aspects which, as mentioned, should not preclude their implementation. Moreover, NGMSs have been successfully combined with traditional instrumentation but have not yet been validated as alternative (or even substitute) techniques to the latter, especially for purpose of legislative compliance. For these reasons the NGMSs must be used only by applying rigorous protocols that guarantee the quality of data obtained. Considering the main advantages and disadvantages highlighted in this work, although accurate measurements are very important for monitoring environmental and occupational exposure, depending on the reason behind the monitoring, some pros may outweigh the cons. Considering the advantages and the criticalities that emerged from the systematic review of the scientific literature, to have the least impact on the routine of the mentioned subjects and to be as reliable as possible, the device that we intend to develop must necessarily be miniaturized and able to upload data to a *cloud* platform. In this way, the development of a dedicated *Mobile App*, served by *Bluetooth* technology, will be of fundamental importance. This use will also allow the acquisition of GPS data and therefore the georeferencing of exposure concentrations, a fundamental aspect for including the use of these technologies in risk management and behavioral modification processes. The use of increasingly advanced monitors and sensors will soon be applied, once the measurements have been validated and the wireless sensor networks (WNS) systems have been implemented, also and above all in occupational studies where the concentrations of airborne pollutants tend to be higher, the substances are more dangerous and the risks for human health are consequently greater. Considering the versatility and the wide range of application of the technologies in question, the hope is that these will be validated and used as soon as possible in the risk assessment process in the occupational field.

CONCLUSIONS

The use of new technologies (NGMSs) for the environmental and occupational exposure assessment to airborne chemical agents appears to be increasingly widespread within the scientific community, alongside the use of traditional instrumentation that allows the correction of any errors of the measurements. The continuous growth of interest in this topic is a symptom of the fact that we are going in the right direction to obtain increasingly reliable and performing tools capable of being used in a wide range of studies, characterized by different experimental designs. The device that we aim to develop will be able to fill several gaps which, differently, through the use of traditional instrumentation, would negatively affect the measures and make monitoring campaigns more difficult. The main advantages of this instrumentation are the high spatio-temporal resolution of the data acquired, the possibility to interconnect the sensors building up sensors networks (WSN) and the very low impact on the daily routine of the investigated subjects.

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