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Electronic Nose Technology and its Applications

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Abstract: In the past decade, Electronic Nose instrumentation has generated much interest internationally for its potential to solve a wide variety of problems in fragrance and cosmetics production, food and beverages manufacturing, chemical engineering, environmental monitoring and more recently medical diagnostic, bioprocesses and clinical diagnostic plant diseases. This instrument measure electrical resistance changes generated by adsorption of volatiles to the surface of electro active- polymer coated sensor- unique digital electronic fingerprint of aroma derived from multi-sensor- responses to distinct mixture of microbial volatiles. Major advances in information and gas sensor technology could enhance the diagnostic power of future bio-electronic nose and facilitate global surveillance mode of disease control and management. Several dozen companies are now designed and selling electronic nose units globally for a wide variety of expending markets. The present review includes principles of electronic nose technology, biosensor structure and applications of electronic nose in many fields. *Copyright © 2009 IFSA.*

Keywords: Electronic Nose, Biosensor, Clinical diagnostic, Microbial volatiles

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1. Introduction

There is an increasing world-wide awareness that bionics and artificial intelligence will play an important role in many aspects of human activity. Medical and microbiology will be no exception, new socio-economical factors and the need of an evolving global community are demanding the development and application of new intelligent diagnostic and therapeutic near patient or home-based devices to control disease more effectively [22]. In the field of clinical microbiology current techniques generally require 24–48 h to identify and characterize a pathogenic microorganism following a series of biochemical tests. Although new molecular biological and serological tests have been introduced recently, they still have not re-placed cultural methods and microscopy. Increased capital cost, need for highly skilled personnel. Complex volatile mixtures are released during microbial interaction with the host tissue or media [25]. Later in the 1970s gas chromatographic techniques were used to study the liberation of microbial volatiles over the headspace of clinical specimens, biological fluids and artificial media. In recent years some elegant analytical techniques, such as pyrolysis mass spectrometry have been applied, sometimes in combination with artificial intelligence software. However, previous methods were characterized by increased capital cost, laborious procedures and required well-experienced personnel [14].

The first model of an intelligent electronic gas-sensing model was described by Persaud and Dodd in 1982 [26]. Since then a significant amount of gas-sensing research has been focused on several industrial applications. Unlike other analytical instrument, this device allows the identification of organic samples without having to identify individual chemical components within the volatile mixture and avoid operator fatigue. Agricultural and food industries have utilized electronic nose technology to measure aroma and food quality, storage life, freshness, agricultural waste detection, recognition of organic chemicals, diagnosis of plant disease and many other applications [36]. Recently, some novel microbiological applications have been reported, such as the characterization of fungi [29, 12], bacteria [30], the identification of leg ulcer profiles and the discrimination between *Helicobacter pylori* and other gastroesophageal isolates [25]. In this review we describe Electronic Noses system and their applications for microbial detection in field of Health care, Food technology, Environmental and Plant pathology.

2. Electronic Nose System

Electronic Nose is a smart instrument that is designed to detect and discriminate among complex odours using an array of sensors. The array of sensors consists of a number of broadly tuned (non-specific) sensors that are treated with a variety of odour-sensitive biological or chemical materials. This instrument provides a rapid, simple and non-invasive sampling technique, for the detection and identification of a range of volatile compounds [14]. The key function of an electronic nose is to mimic human olfactory system (Fig. 1). The human nose is still consideration the primary tool employed in industry to characterize the odour of a variety of consumer products. In 1961 Moncrieff developed the first mechanical olfactory instrument followed by several other attempts such as the study of redox reactions of odourants at an electrode. However the first model of an artificial electronic odour detection system was described during the early 1980s and attempted to mimic some basic functional characterization of human olfactory system [27]. Mammalian receptors have been replaced by partially selective and significantly sensitive inorganic or organic gas transducers that interact in a unique way with individual gas molecules or complex odour mixtures and transform chemical interaction into electrical signal [22]. Several types of sensory material are currently used in artificial nose technology such as metal oxide, conductive polymers, piezoelectric crystal and fibre optics [11].

An odour stimulus generates a characteristic fingerprint from this array of sensors. Patterns or fingerprints from known odours are used to construct a database and train a pattern recognition system so that unknown odours can subsequently be classified and/or identified [22]. Typically an electronic nose consists of three elements: a sensor array which is exposed to the volatiles, conversion of the sensor signals to a readable format and software analysis of the data to produce characteristic outputs related to the odour encountered (Fig. 1). The output from the sensor array may be interpreted via a variety of methods such as pattern recognition algorithms, principal component analysis, discriminant function analysis, cluster analysis and artificial neural networks to discriminate between samples. This technology is a user-friendly, inexpensive and intelligent laboratory diagnostic device [32].

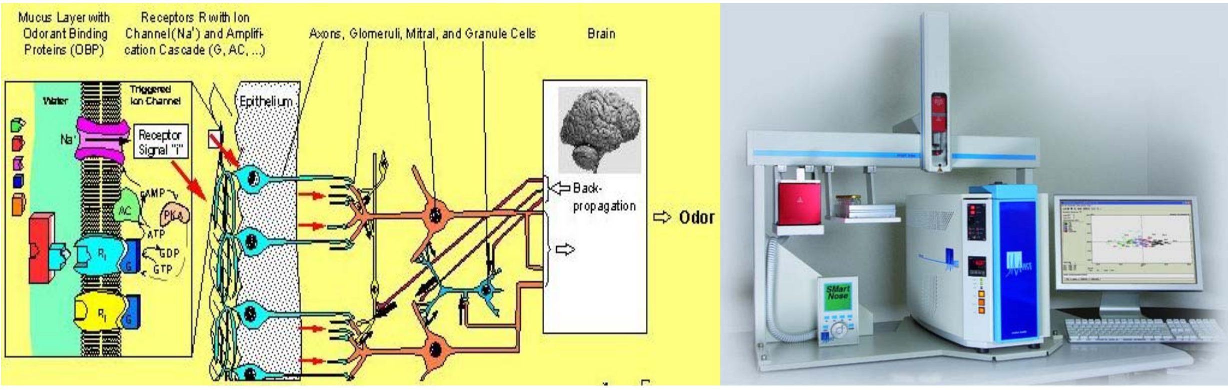

Fig. 1. Schematic representation of human and artificial olfactory system [22] and Generalize structure of electronic nose.

2.1. Volatiles as Biomarker

When conditions are favorable and a nutrition source is present, microbial organisms such as fungi and bacteria can grow and generate volatile organic compounds (VOCs) including different alcohols, aldehydes, ketones, aromatic compounds, amines, terpenes, chlorinated hydrocarbons and sulphuric compounds while metabolizing nutrients, and those volatiles have been used as indicator of microbial growth [29]. Volatile production due to microbial interaction with organic media and biological has been well studied and reported since the beginning of the 19th century. Maasren (1899) described four bacterial species, which were able to produce odours of esters, mercaptan, and pineapple when cultured in the same meat peptone bouillon medium. Even symbiotic cultures of several bacteria produced complex characteristic odours when grown in complex organic media. Omelianski (1923) was one of the first to study naturally generated microbial odours. A new group was introduced called 'aroma producing micro-organisms' and included: (a) odoriferous yeasts, (b) acetic acid bacteria, (c) lactic acid bacteria, (d) butyric putrefactive bacteria, and (e) pathogenic species such as *Mycobacterium tuberculosis* and *Pseudomonas aeruginosa*, able to liberate a pleasant smell [25]. Smell can be used to diagnostic disease and has been used by both the Greek and Chinese since 2000 BC. Hippocrates in 400 BC had recognized the diagnostic power of odour, "*If a patient pass blood, pus and scales in the urine and if it has a heavy smell, ulceration of the bladder is indicated", "In persons affected with phthisis, if the sputa which they cough up, have a heavy smell when poured upon coals, the case will prove fatal*" (Hippocratic writings, Aphorisms IV and V), [9, 22].

Recently, the potential for use of volatiles production pattern as a tool for identification of early clinical diagnosis of a number of disease including breast and lung cancer, cardiovascular disease, respiratory infection, diabetes, leg ulcer streptococcal and acute asthma has been recognized [23, 13].

2.2. Biosensors

A biosensor can be defined as a compact analytical device incorporating a biological or biologically derived sensing element (such as an enzyme, antibody, microbe or DNA) either integrated within or intimately associated with a physicochemical transducer [21, 7]. Upon interaction with a chemical species, the physicochemical properties of the sensing layer (mass, optical properties, resistance etc) change and this are detected by the transducer. The changes are then converted into an electrical signal which is then processed. The transducer may be optical (e.g., optical fibre), electrochemical (e.g., ion-selective electrodes), heat-sensitive (e.g., calorimetric) or piezoelectric (e.g., acoustic wave), [33, 15]. The main parts of a typical biosensor are shown in Fig. 2.

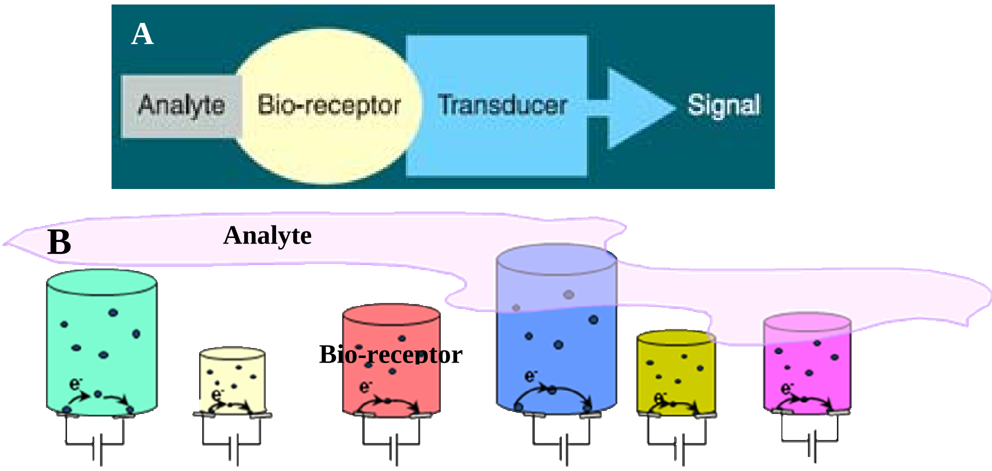

Fig. 2. (A) The main parts of a typical biosensor, (B) A sensor array, Each polymer changes its size and therefore its resistance, by a different amount and making a pattern of the change.

In addition biosensors can be classified into two broad categories: sensors for direct detection of the target analyte and sensors with indirect, labeled, detection. Direct detection biosensors are designed in such a way that the bio specific reaction in directly determinate in real time by measuring the physical changes induced by the complex formation. Indirect detection biosensors are those in which a preliminary biochemical reaction takes place and the products of that reaction are then detected by a sensor. Some type of biosensors such as electrochemical, optical and piezoelectric will be given priority as they are having great impact upon the detection of microbes [15].

2.2.1. Electrochemical

These biosensors are usually based on ion-selective electrodes. These devices measure the change in ion concentration during a reaction. Three main types of ion-selective electrodes are often used in biosensors: normal glass pH electrodes, glass pH electrodes coated with a selective gas-permeable membrane and solid-state electrodes consisting of a thin membrane of a specific ion conductor. It is also possible to use metal oxide semiconductors (MOS) which can be used to measure charge on a surface which will cause a current flow proportional to the charge. These biosensors have been widely used for bacterial analyses. Examples include the detection of bacterial contamination in milk using an L-lactate biosensor, bacterial growth and sequence-specific biosensing of DNA [7].

2.2.2. Optical

Optical biosensors are usually based upon optical fibers or Surface Plasmon Resonance (SPR), although it is common to find luminescence, fluorescence and absorbance also being used. Optical fibers are long, thin strands of pure glass. Reported uses of these biosensors include the detection and quantification of bacteria in meat and poultry e.g. *Salmonella*, *Escherichia coli* and *Listeria*. Many of these are based on the use of antibodies for the specific recognition of the pathogen. By immobilizing several antibodies on different fibre probes, it is possible to detect several bacterial species simultaneously [8, 11].

2.2.3. Piezoelectric-based Acoustic Wave Devices

Acoustic wave devices have been commercially used for more than 60 years with the telecommunications industry being the largest consumer, primarily in the mobile phone sphere. These devices are sensitive to changes in mass, density, viscosity and acoustic coupling phenomena. As the acoustic wave propagates through or on the surface of the material, the velocity and /or amplitude of the wave are changed. Changes in the velocity can be monitored by measuring the frequency of the sensor which can then be related to the physical parameter under consideration. Piezoelectric substrates include quartz, lithium tantalite, lithium niobate, silicon carbide and gallium arsenide. Several researchers have reported on the use of acoustic wave biosensors to detect microbes [7, 6].

Sensor technology has developed rapidly over the past decade and this has resulted in a range of different sensor formats and the development of complex microarray sensor devices. In the specific area of electronic nose systems, several different physicochemical techniques have been used to produce sensor arrays for odour characterization. The Table 1 gives further examples of the various transducers.

2.3. Signal Processing

The interaction of the volatile compounds and the conducting polymer surface produced a change in electrical resistance and then produced a signal which can be measured and analyzed by data processing system. Data processing techniques, used to perform detection, classification and description functions associated with the e-noses often include.

Table 1. Transducers used in biosensor development.

Category	Principle	Examples
Electrochemical	(a) potentiometric: dependents on changes in potential of a system at a constant current (b) amperometric: detects changes in current as a function of concentration of electroactive species	Ion selective electrodes, ion selective field effect transistors. Solid electrolyte gas sensors, electronic noses
Optical	Link changes in light intensity to changes in mass or concentration, therefore, fluorescent or colorimetric molecules must be present	Optical fibres, surface Plasmon resonance, absorbance luminescence
Piezoelectric	Sensitive to changes in mass, density, viscosity and acoustic coupling phenomena	Surface acoustice wave sensors
Thermal	Detect changes in temperature	Calorimetric sensors

Principal Components Analysis (PCA), Cluster Analysis (CA), Discriminant Function Analysis (DFA), Neural Network and Fuzzy Logic [9]. Improvement and integration of new techniques are currently developing in order to enhance the accuracy of the prediction models. The systems optimizing knowledge extraction from e-nose are highly sophisticated and need to perform mathematical/statistical methods to implement and improve data analysis. This application area is a very complex area of research in different fields such as medicine and biology [5].

3. Applications of Electronic Nose

The potential applications for the electronic nose technology are very extensive. Electronic nose technology has been applied to a range of food science [5, 34, 20], medical [22, 32] and environmental applications [2, 3]. In addition this technology offers great potential for the detection of different microbial species. Some chemical products are specific to fungal and bacterial species and are commonly used as a useful diagnosis tool. The advantage of the e-nose technology is that it can be used for effective monitoring in a storage situation, especially if linked to a real time neural network which has information on the volatile patterns from non-spoiled paper material [4]. It could then be used to effectively provide a warning of when conditions may become compromised and effective management could be then employed for preventing loss of valuable cultural material. This has already been successfully demonstrated for detection of mouldy grain and growth of moulds in libraries, archives and museums [20]. The field of sensor technology is also advancing rapidly and other sensor arrays are now available with better sensitivity and stability in different abiotic environments.

3.1. Electronic Noses for Medicine

In many cases, infection with microorganisms produces a change on the smell of person, which can be specially noticeable on the breath, in the urine or the stool, such changes have been commonly used as an aid to diagnosis of disease and some countries smelling the patient or the body fluids of patient was, and still is, an important tool in diagnosis [13, 18]. The diagnosis power of odour in medicine is vary old practice which in being rediscovered due to new advances in gas sensor technology and artificial intelligence. Several diseases have been noted in the past to produce odour or volatiles characteristic of the disease state. Intelligence gas sensor technology has been applied in several areas of clinical practice, from bacteria detection UTI, *Mycobacterium tuberculosis* (TB) and gastric diagnosis [22, 23], as well as, detection of certain bacterial pathogen infections in clinical specimens such as vaginal fluids, urine and leg ulcer specimens [9].

3.2. Electronic Noses for the Food Industry

Currently, the biggest market for electronic noses is the food industry. Applications of electronic noses in the food industry include quality assessment in food production, inspection of food quality by odour, control of food cooking processes, inspection of fish, monitoring the fermentation process, checking rancidity of mayonnaise, verifying if orange juice is natural, monitoring food and beverage odours , grading whiskey, inspection of beverage containers, checking plastic wrap for containment of onion odour, and automated flavor control to name a few [34, 31, 10]. In the food-processing industry quality assurance systems need to be rapid and range from organoleptic measurement to microbiological surveys. Generally, qualitative assessment of food spoilage is made by human sensory panels that evaluate air samples and discriminate which food products are good or unacceptable. Bacterial contamination of food and drinks can generate unpleasant odours and toxic substances. Therefore, different industries are interested in the application of the e-nose both for monitoring of storage quality degradation and for detecting microbial contaminants [19]. One of the earliest reports of e-nose technology applied to food analysis was described by Rossi *et al.,* in 1995. Early detection of milk spoilage as well as different concentrations of spoilage bacteria and yeasts was also investigated. The results of these studies showed that, using an e-nose system, it could distinguish between volatile profiles of different species inoculated in milk-based media after two and five hours of incubation [1]. As well as bacteria many fungal species were described to play an important role in the degradation of foodstuffs. Different species have been isolated from food and some studies have been performed on different fungal species isolated from cereal grain and mouldy bread. Electronic nose was used for detection of these contaminations in many cases. In some instances electronic noses can be used to augment or replace panels of human experts. In other cases, electronic noses can be used to reduce the amount of analytical chemistry that is performed in food production especially when qualitative results will do [5].

3.3. Electronic Noses for Plant Disease Diagnosis

The Electronic Nose technology is novel and in its infancy for application in plant pathology. A rapid, sensitive, specific, nondestructive and easy-to-use technique such as the Electronic Nose could be utilized for detection and identification of plant pathogenic bacteria in plant diagnostic clinics and quarantine laboratories. The use of the electronic nose for the identification of plant pathogens was reported previously as abstracts [37, 17]. The discrimination of seven species of plant pathogenic bacteria (*Acidovorax avenae* subsp. *citrulli*, *Agrobacterium tumefaciens*, *Clavibacter michiganensis* subsp. *michiganensis*, *Erwinia amylovora*, *Pseudomonas syringae* pv. *tomato*, *Ralstonia solanacearum*, and *Xanthomonas campestris* pv. *vesicatoria*) by measuring the volatile compounds produced from pure cultures has been performed using an E- nose and Discriminant Function Analysis [16]. Many microbes have effects on forest health and ecosystem functions because they include causal agents of tree mortality, forest diseases, wood decay and lumber defects of importance in ecosystem and timber management, and in the manufacture of forest products. Within the field of forest pest management, electronic nose has proven useful in detection of bacterial wet wood infections in cottonwood, the detection and identification of fungal forest pathogens (e.g. *Ceratocystis fagacearum*), and the discrimination of wood decay fungi in wood samples [37, 35]. Some Fungi such as *Aspergillus* species is one of the most important factors that influence deterioration of library and museum materials. Electronic nose was used for detection and differentiation ox xerophilic *Aspergillus/Eurotiom* species on different types of paper samples in library, as well as for detection of the growth of moulds in library, archives and museum [4].

3.4. Electronic Noses for Environmental Monitoring

Environmental applications of electronic noses include analysis of fuel mixtures, detection of oil leaks, testing ground water for odours, identification of household odours, identification of toxic wastes, air quality monitoring, and monitoring factory emissions [2, 3].

4. Conclusions

In this review we have described the applications of electronic odour sensing systems for microbial detection in the fields of health care, food technology, environmental and plant pathology. Published literature is considerable and explores different experimental conditions to develop and implement these new analysis methods. Electronic noses are electrical resistance modulated sensing devices containing a sensor array capable of producing a digital fingerprint of volatile organic compounds released from any source. Conductive polymer sensor array take advantage of differential responses of different conducing plastics (within each sensor) to various chemical species in the sample headspace by producing a unique electronic aroma signature pattern (EASP) specific to the analyte mixture. The response of each sensor is based on the collective effect of the entire mixture of components in the headspace on electrical resistance changes generated by adsorption of analyte to the sensor. Sensor adsorption is determined by the specificity of chemical types, quantities and molar ratios of chemicals present in the sample mixture [36]. Biosensors are making a great impact on the development of rapid, sensitive assays for the detection of microorganisms. Although much success has been achieved in terms of research, commercial development has been slow. Kits are now available for several organisms such as *Escherichia. coli* and *Salmonella typhimurium* and it is hoped that more will become available shortly. New developments include integrated systems the use of molecular beacons and nanosensor production. These should ensure even more rapid and specific detection. The potential development of this technology coupled with remote data acquisition and central processing powered by hybrid intelligence systems could make this appreciate world-wide [32].

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
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