

A BIOLOGICALLY-INSPIRED ARTIFICIAL OLFACTORY MUCOSA

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Abstract: The ability of an electronic nose system to detect and discriminate between different complex odours still lags behind that of the human nose. Here we report on an artificial olfactory mucosa, which mimics the basic structure and operation of the nasal cavity, and show its ability to generate novel spatio-temporal odour signals. We believe that this approach could lead to superior electronic nose technology.

Keywords: Electronic noses; chemical microsystems; biomimetic sensors.

INTRODUCTION

Over the last two decades there have been considerable advances in our understanding of sensory mechanisms within the human olfactory system. In parallel, research has also been directed upon its electronic counterpart (commonly known as the electronic nose) that seeks to mimic this sense. Though significant progress has been made in developing new types of sensing materials and pattern recognition techniques, little effort has been devoted to emulating the way odours are transported inside the nasal cavity and more specifically across the olfactory mucosa [1,2]. Research has shown that the olfactory mucosa, which comprises of a mucous layer and olfactory epithelium, behaves like a gas chromatograph. Hence this “nasal chromatograph” acts to delay, in time, chemical components within odours as they are transported along the nasal cavity. Thus, as an odour traverses this nasal cavity, receptor cells within the olfactory epithelium and below the mucous layer, produce both spatial and temporal information. This information relates to the magnitude of the receptor response, proportional to the quantity of a chemical component, and the temporal delay caused by the interaction of the odour with the mucous layer. This combined spatial-temporal data could be an important factor which helps the biological system outperform the artificial electronic nose. Our aim here is to build a new type of electronic nose or “artificial olfactory mucosa” that mimics the human counterpart and is capable of generating these spatio-temporal chemosensory signals [3].

ARTIFICIAL OLFACTORY MUCOSA

Figure 1 shows the basic configuration of our artificial mucosa. As stated above, the olfactory mucosa comprises of an array of sensors distributed around and along the mucous coated nasal cavity. Hence a spatio-temporal map of an odour is created. In this project, for simplicity, the sensors have been distributed in a row along a channel to emulate the olfactory mucosa.

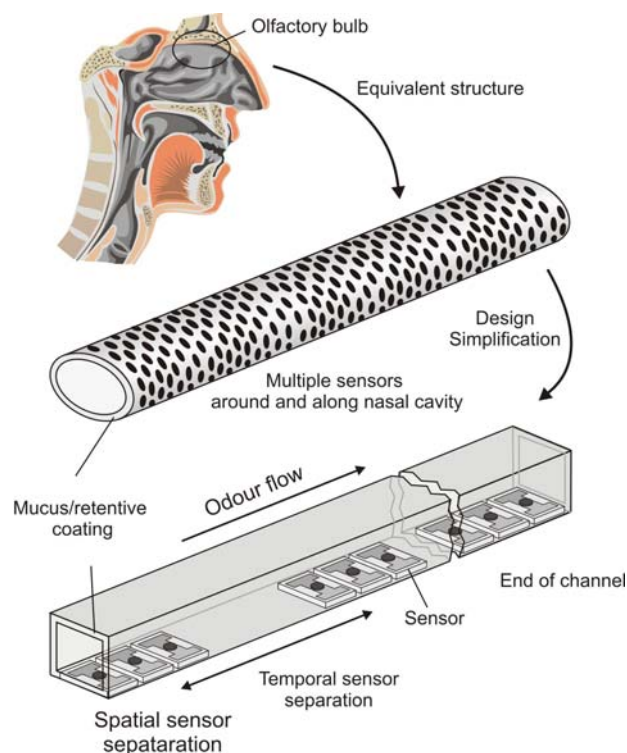


Figure 1. Design concept of artificial mucosa.

The artificial mucosa comprises of a 0.5 mm × 0.5 mm × 2.4 m long channel and an array of 40 discrete chemoresistive sensors. These sensors were fixed to a PCB on top of which was placed a lid containing the channel. The sensors were fabricated using a simple in-house process with each device being 2.5 mm × 4.0 mm in size and consisting of a pair of thin gold electrodes on top of a SiO₂/Si substrate. The electrode length was 1.0 mm with an inter-electrode gap of 75 μm. A top SU-8-10 (Microchem, UK) layer was used for passivation with openings left for deposition of the sensing materials and contacts. Polymer/carbon black composite materials were chosen as the odour sensitive coatings. These combine a non-conducting polymer with carbon nano-spheres that endows good electrical conduction to the blend. The sensing materials were chosen due to their rapid (ms) response time, ease of deposition, room temperature operation and the wide variety of available polymers. An 80:20 polymer/carbon ratio

mix was used in the production of the coatings. More details on the polymer deposition process can be found in [4]. Figure 2(a) shows an individual sensor after coating. After deposition, the sensors were mounted into recesses machined into a PCB, hence the sensors were flush with the surface. The individual sensor devices were then wire-bonded on to the PCB. Figure 2(b) shows the sensors mounting.

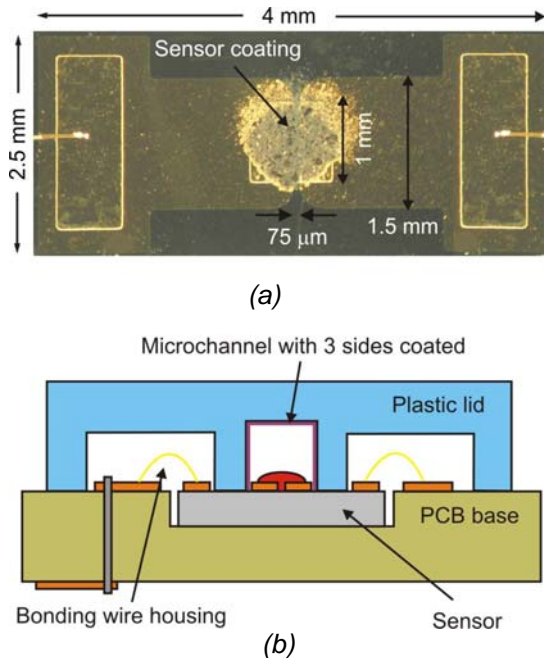


Figure 2. Photograph of coated sensor (a) and mounting into sensor system (b).

The lid was fabricated from Perspex and machined with a 0.5 mm square channel. The lid was aligned with the base and held together by screws. Finally, the edges and slots were filled with sealant (3145 MIL-A-46146, Dow Corning, UK) to obtain a leak-free system. Table 1 lists the different sensing materials and the sensor position along the channel. These sensors emulate the function of the olfactory epithelium within the olfactory mucosa.

Two identical lids were fabricated, one for coating with a retentive material and the other left without as a reference. The retentive layer used here was Parylene C deposited by an evaporation technique using a commercial machine (PDS 2010 Labcoater™ 2, Specialty Coating Systems, Indianapolis, USA). This material has previously been shown by Hesketh *et al.* to have stationary phase like properties [5]. The machine performs deposition under vacuum and at room temperature. Here a retentive coating thickness of 10 μm was used throughout the experiments.

Figure 3 shows the fully assembled system with an uncoated channel on a PCB interface and a standard 64 dual-in-line pin IDC (far left side). Hence, this combination mimics the basic structure of the olfactory mucosa.

Table 1: Sensors number, sensing material and position

Sensor No.	Position (mm)	Polymer
S1, S11, S26, S36	10, 570, 1620, 2180	Poly(ethylene-co-vinyl acetate) (PEVA)
S2, S12, S27, S37	30, 590, 1640, 2200	Poly(styrene-co-butadiene), (PSB)
S3, S13, S28, S38	50, 610, 1660, 2220	Poly(ethylene glycol), (PEG)
S4, S14, S29, S39	70, 630, 1680, 2240	Poly(caprolactone), (PCL)
S5, S15, S30, S40	90, 650, 1700, 2260	Poly(vinyl pyrrolidone), (PVPD)
S6, S16, S21, S31	240, 930, 1260, 1950	Poly (9-vinylcarbazole) (PVC)
S7, S17, S22, S32	260 950, 1280, 1970	Poly (vinyl pyrrolidone) (PVPD)
S8, S18, S23, S33	280, 970, 1300, 1990	Poly (bisphenol A carbonate), (PBA)
S9, S19, S24, S34	300. 990, 1320, 2010	Poly (sulfane), (PSF)
S10, S20, S25, S35	320, 1010, 1340, 2030	Poly (chloro P xylylene), (PCX)

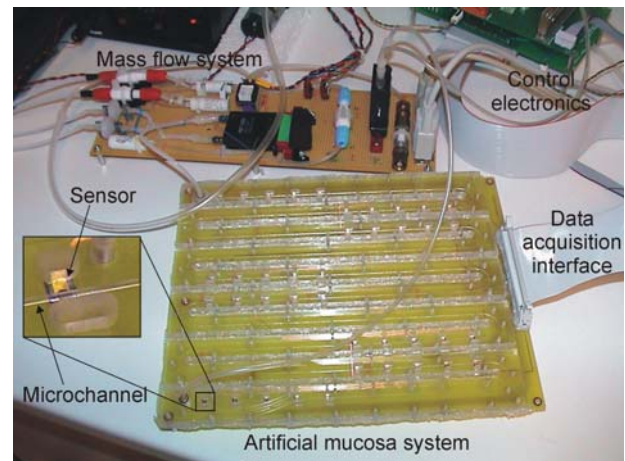


Figure 3. Photograph of artificial olfactory mucosa.

For testing, the system was connected to a custom made mass flow system (as also shown in figure 3). The resistance of the sensors was measured by using the sensor as the feedback resistor of an operational amplifier circuit in an inverting configuration. The reference input resistor was connected to a -2.5 V reference voltage source to produce a positive output, then sampled by a 16-bit analogue to digital converter (ADC). More details can be found in [6].

EXPERIMENTATION AND RESULTS

Preliminary experiments were carried out with simple polar and non-polar odours, namely, ethanol and toluene vapour in laboratory air (25 ± 2°C, humidity 40 ± 5% r.h., 10 second pulse, flow rate 25 ml/min, test length 5 min). Here laboratory air was used to more closely mimic real life conditions. Figure 4 shows the spatial response of the first 10 (S1-S10) sensors to the same pulse of ethanol

vapour in air. This demonstrates the capability of the system to generate spatial signals of different response profiles and magnitudes (similar to traditional electronic nose).

In order to test the systems ability to create temporal signals, the artificial mucosa was tested with both coated and uncoated lids. Figure 5 shows the response of PEVA sensors at the beginning and end of the channel to toluene and ethanol vapour in air for (a) an uncoated lid and for (b) a coated lid.

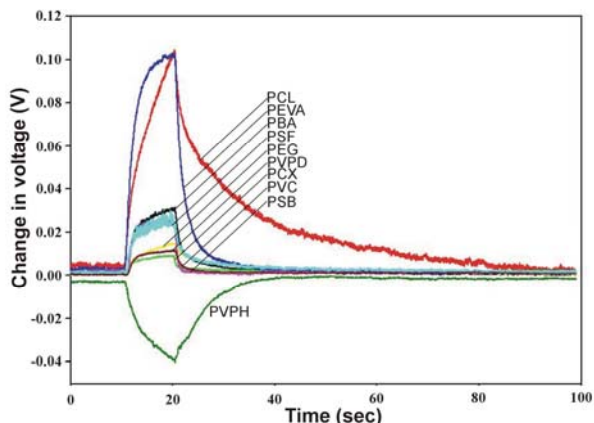


Figure 4. Different (spatial) responses of 10 different polymer sensors to a simple odour pulse (ethanol) in air.

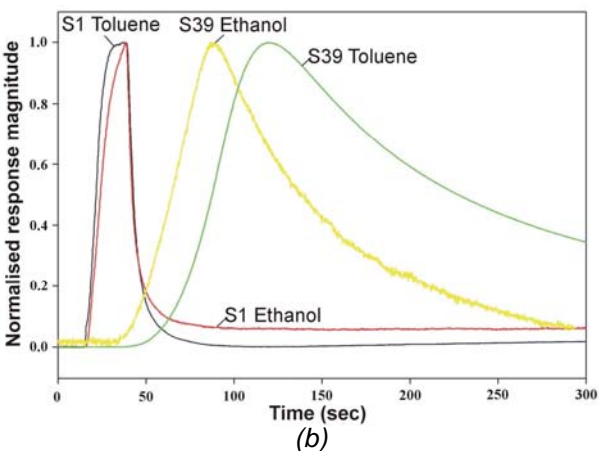
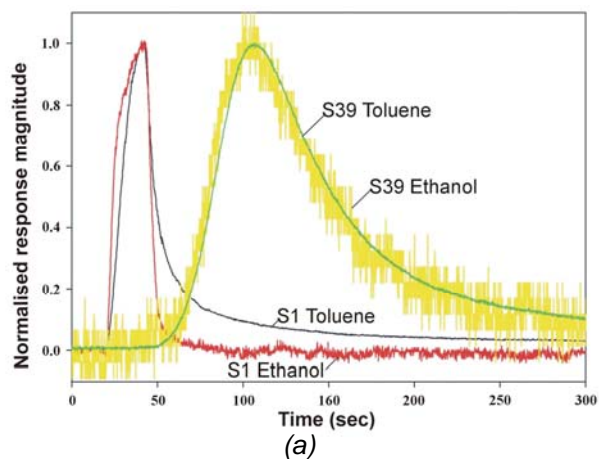


Figure 5. Temporal response of the artificial mucosa with (a) uncoated lid and (b) coated lid for a PEVA sensor to toluene and ethanol vapour in laboratory air.

For these temporal measurements the sensors output had been normalised, hence the magnitude information is removed.

It is clear from the data shown in Figure 5 that two different mechanisms take place within the sensor system. Figure 5(a) shows the effect of pulse broadening through the channel. Thus, as the vapour pulse travels down the channel, its front broadens out by simple diffusion. This figure also shows that the time at which the vapour pulse reaches the final sensor, for both toluene and ethanol vapour, is the same, hence there has been no differential retention of the vapour. Figure 5(b) shows that both pulse broadening and, most importantly, a differential retentive delay to the vapours is observed. Thus, even though the first sensor responds at the same time to the toluene and ethanol pulses, there is a marked difference in delay times at the end of the channel. This can only be explained by the retentive nature of the channel coating. Temporal delays of 58 s and 92 s for ethanol and toluene vapour respectively have been measured (calculated from the time taken for the first and last sensor to reach 50% of its final value). These results show the ability of the artificial mucosa to generate spatio-temporal signals, which differs significantly in nature from current electronic-nose technology.

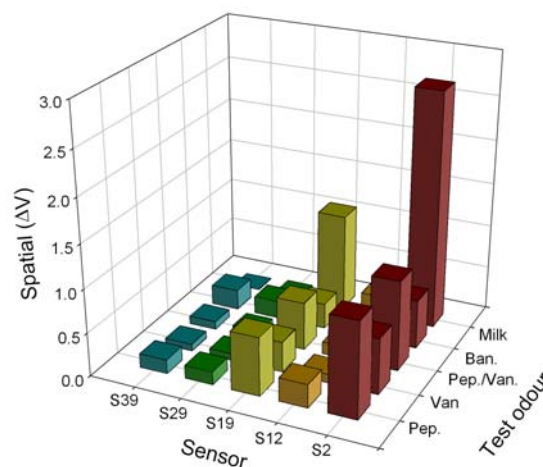
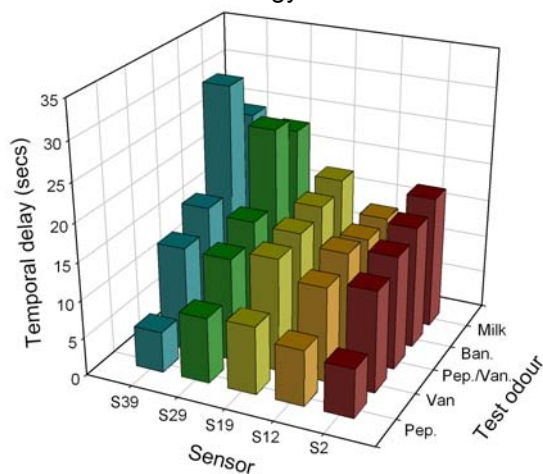


Figure 6. Temporal and Spatial responses of sensors along channel to test odours

In order to further evaluate the ability of the system to separate odours, additional experiments were carried out using complex odours – specifically peppermint, vanilla, 50:50 mix by volume of these, banana and milk. Experimental conditions were as before. For analysis only 5 sensors (S2, S12, S19, S28 and S39) were used, taking both the spatial (using the maximum differential change in voltage) and temporal (using the time for each sensor to achieve 50% of its final (spatial) response) information.

For each sample 10 replicate measurements were performed. Figure 6 shows the spatial and temporal responses of these sensors to the test odours. The data were used to perform a principal components analysis (PCA). Three PCA plots were produced, namely, one for the spatial information, one for the temporal, and one combining these two data-sets. Figure 7(a) shows the PCA plot for the spatial data and figure 7(b) shows the combined spatial and temporal data. In both cases near complete linear separation (including the temporal data not shown here) is achieved. The only exception was for milk and banana using the spatial data-set as can be seen in figure 7(b). When both the spatial and temporal data are used a marked improvement in the cluster separation is observed.

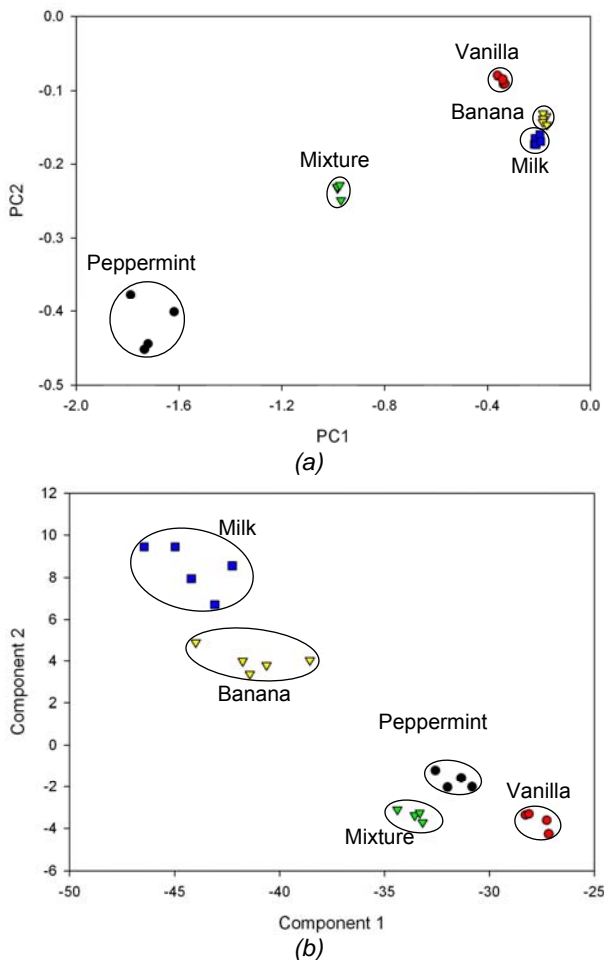


Figure 7. PCA analyses of (a) spatial data and (b) temporal and spatial data to peppermint, vanilla, mixture, banana and milk (mixture is 50:50 mix by volume of peppermint and vanilla).

These results clearly show that spatio-temporal signals can be generated for different simple and complex odours. In addition, it has been observed that improved separation is possible by using the combined spatial and temporal data over either set alone, thus emulating the nasal chromatography principle exhibited in biological olfactory system.

CONCLUSIONS

Here we report on the development of a novel artificial olfactory mucosa that may enhance the discrimination capability of current electronic nose technology. This principle is based on the olfactory's ability to create both spatial, as with a normal e-nose, and temporal, as with GC, signals. This is possible due to the distribution of sensors along the nasal cavity exploiting the "nasal chromatograph" effect. Using this concept a system combining 40 polymer-composite resistive sensors of 10 different tunings placed along a 2.4 m long polymer-coated channel has been fabricated. This system has been tested with both simple and complex odours in order to evaluate the system. Preliminary results show that our system is capable of generating spatio-temporal signals for simple and complex odours with delays up to 100 seconds. In addition, we have shown that these signals can be used for classification (with a linear technique) complex odours, and that this combined signal gives improved separation over either signal alone.

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