Self-Healable Sensors Based Nanoparticles for Detecting Physiological Markers via Skin and Breath: Toward Disease Prevention via Wearable Devices

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1. Experimental Details

1.1. Synthesis of the self-healing polymer substrate:[1]

4-Aminophenyl disulfide (750 mg, 3.0 mmol) was dissolved in 1 mL tetrahydrofuran (THF) under ultrasonic conditions. Poly(propylene glycol), tolylene 2,4-diisocyanate terminated, M_w= 2300 (5.1 g, 2.2 mmol) was added and stirred constantly for 15 min. The resulting viscous mixture was transferred to a Teflon mold and completely degassed under vacuum for 15 min. Finally, the liquid was cured for 48 h at 75°C under vacuum, yielding a product that was a yellowish transparent elastomer. Details of the healing mechanism for the polymer can be found in previously publications.[1] Briefly, reversible hydrogen (dash line in left side of Figure S1) and covalent (dash line in right side of Figure S1) were formed inside the polymer. After the polymer was scratched, hydrogen and/or covalent bonds were broken. Due to the reversible of hydrogen and covalent bond, the broken bond will automatically recovered and result in the damaged polymer self-healed to its initial state.
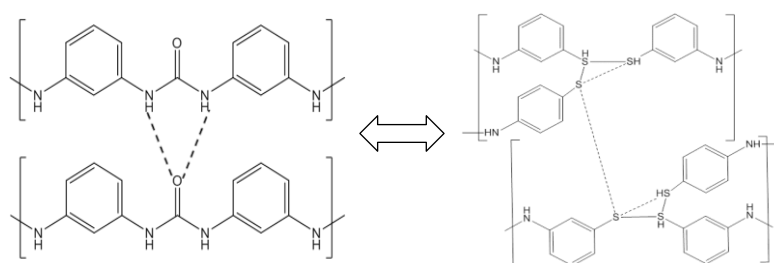
Figure S1. Proposed structural formula of polymer substrate containing reversible hydrogen and covalent bonds.

1.2 Preparation of the sh-µAg-PU electrode

1 g silver µAg (5-8 µm, ≥ 99.9% trace metals basis) powder was dispersed in 220 µL polyurethane diol solution (Mw= 320) for 15 min using a homogenizer. The dark grey viscous µAg-PU composite was degassed under vacuum for 15 min, yielding a highly conductive (~20 to 30 Ω) paste.

1.3 Synthesis of the molecularly functionalized gold nanoparticles (GNPs)

Molecularly-functionalized 3-5 nm (in diameter) gold nanoparticles were prepared by a modified two-phase method.[2] 3-ethoxythiophenol, benzylmercaptan, tert-dodecanethiol, hexanethiol and decanethiol were purchased from Sigma-Aldrich and used as organic ligands. $AuCl_4^-$ was transferred from an aqueous $HAuCl_4 \cdot xH_2O$ solution (25 ml, 31.5 mmol/L); Sigma-Aldrich) to a toluene solution by 80 ml 34.3 mmol/L phase-transfer reagent, tetraoctylammonium bromide (Sigma-Aldrich). After the organic phase had been isolated, an excess of organic ligands were added to the solution. The molar ratio of thiol : $HAuCl_4 \cdot xH_2O$ was varied from 1 : 1 to 10 : 1 depending on the kind of thiol in order to prepare a monodispersed solution of gold nanoparticles of average size (3-5 nm). After vigorous stirring of the solution for 10 min, an aqueous solution of reducing agent, $NaBH_4$ (Sigma-Aldrich), in a large excess (25 ml, 0.4 mol/L, ice-cooled) was added. The mixture was stirred at room temperature for >3 h, producing a dark brown solution of the thiol-capped gold nanoparticles. The solvent was removed in a rotary evaporator, followed by several washes in ethanol and toluene.

1.4 Fabrication of the self-healable and flexible nanoparticle-based sensor array[1]

For fabrication of a self-healable nanoparticle-based flexible sensor array, a 100 × 100 × 1 mm polymer sheet was prepared as a substrate. A 50 µm non-adhesive paper mask placed onto this substrate was coated with sh-µAg-PU electrodes using a screen-printing method.[1] After removing the mask, the distance between two sh-µAg-PU electrodes was 0.5 mm. Two electrical wires penetrating through the back of the sh-crl-PU substrate were in connection with the sh-µAg-PU electrodes. This structure was evacuated for 30 min before drop-casting 1 µL 50 mg/mL solution of different molecularly-functionalized GNPs onto the groove between the two sh-µAg-PU electrodes. Hence, molecularly-functionalized GNPs were firmly stuck to the substrate, due to the sticky surface of polymer substrate. Finally, the sensor array was stored under vacuum for 1 d before measurement.

1.5 Evaluating the sensor array in monitoring of pressure variation

A MARK 10 ESM301 motorized test-stand was used to apply a strain at a constant speed of 0.05 mms^{-1}. The stress was applied by an upper beam (downward) and supported by bottom beams (stationary), under which the substrate bent. The outer (upper) surface became compressed, while the inner (lower) surface was dilated. In the stretching set-up, the

strain/force was applied between two metal grips on a dog bone sample. The strain was applied as above between metal grips attached to the wider part of the sample, whereas most of the strain was taken by the thinner part of the sample. The forces were measured by an advanced digital force gauge (Mark10, USA). Electrical resistance in these experiments was measured by a Keithley data-logger device (model 2701 DMM) controlled by a custom Labview program. The conversion of gram-force (gf) to gf/cm^2 is: gf/S, where the S is the area of the sensor, in this research the S is 2 cm^2 (length × width: 20 × 10 mm). As for the conversion of gf/cm^2 to mmHg, it can be performed through website: http://www.endmemo.com/sconvert/gf_cm2mmhg.php

1.6 Evaluation of the sensor array toward 11 kinds of VOCs

A Keithley data-logger device (model 2701 DMM) controlled by a custom Labview program was used to sequentially acquire resistance readings from the sensor array and voltage readings from the environmental sensors. A typical exposure cycle involved a 5 min vacuum (<100 mTorr) baseline step, followed by 5 s exposure and 4 min 55s measurement of the test vapor under still conditions, ending with another 5 min vacuum step. Nitrogen and 11 kinds of VOC flow (5 L/min constant flow rate) were alternately introduced into the chamber (Table S1). Four successively increasing concentrations of each VOC, controlled gas concentrations (0.5–20 ppm), were produced by a commercial dynamic liquid injection dilution system (Umwelttechnik MCZ, Germany).[3] The power of the sensor array could be calculated from the equation U^2/R, where the U is the applied voltage on the sensor array (5 V in this case), and R is the resistance of the sensor array after exposure to the target gas.
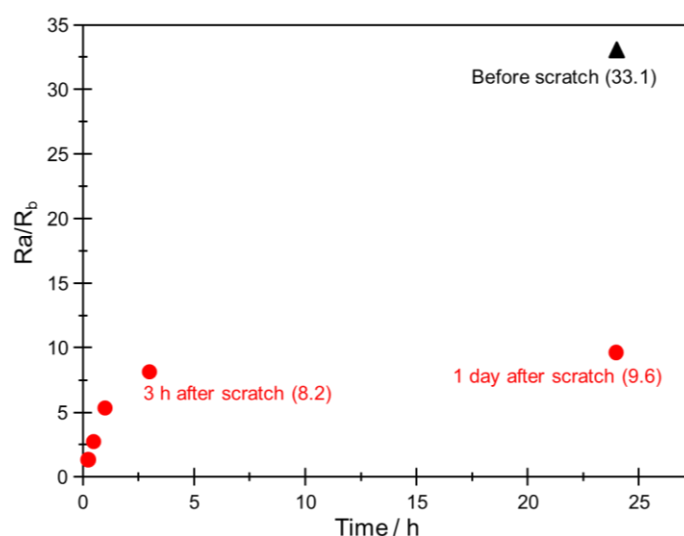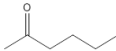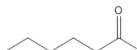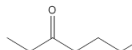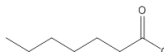

Figure S2. Response of the sensor unit consisting of benzylmercaptan-functionalized GNP film to 20 ppm hexanal in a scratching/healing cycle.
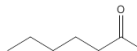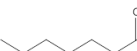
Table S1 Healing period and sensing response (to 20 ppm hexanal) of the molecularly-functionalized GNP at different concentration.

| Ligands-functionalized GNP	3-Ethoxythiophenol functionalized GNP			Benzylmercaptan functionalized GNP			Tert-dodecanethiol functionalized GNP			Hexanethiol functionalized GNP			Decanethiol functionalized GNP		
Concentrations / (mg/mL)	10	20	50	10	20	50	10	20	50	10	20	50	10	20	50
Healing period / h	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Response ($\Delta R_a/R_b$) to 20 ppm Hexanal / %	1.60	2.21	3.05	6.01	15.04	36.77	2.04	4.05	10.94	-4.49	-9.75	-15.63	1.36	3.11	6.78

The healing capability of the sensing films in different concentration is analogous, but their sensing performance is decreased with the decreasing of concentration of the sensing films. The declining of the performance for the sensing films at low concentration can be attributed to the inadequate sensing chemicals for sensing of VOCs (e.g. hexanal).

Table S2 Chemical formula and physical properties of the selected 11 kinds of VOCs found in human breath/skin.

VOCs	CAS NO.	Formula	Boiling point ($^{\circ}C$)	Density (at $25^{\circ}C$) (g/cm^3)	P_0 (at $25^{\circ}C$) (kPa)	Breath/Skin
2-Hexanone	591-78-6		158.1	0.830	1.5	Breath/Skin
Acetic acid	64-19-7		117.9	1.0446	2.1	Breath/Skin
Heptane	142-82-5		98.4	0.6795	6.0	Breath/Skin
Hexanal	66-25-1		160.5	0.8335	1.4	Breath/Skin
n-Hexane	110-54-3		68.7	0.6606	20.4	Breath/Skin
3-Heptanone	106-35-4		170.3	0.8183	0.5	Breath
Heptanotic acid	111-14-8		249.2	0.9181	1.9×10^{-3}	Breath/Skin
Hexanoic acid	142-62-1		205.8	0.929	5.7×10^{-3}	Breath/Skin
Heptanal	111-71-7		152.8	0.8216	0.5	Breath/Skin
Nonanal	124-19-6		209.7	0.8264	3.6×10^{-2}	Breath/Skin
Nonane	111-84-2		151	0.7173	0.5	Breath/Skin
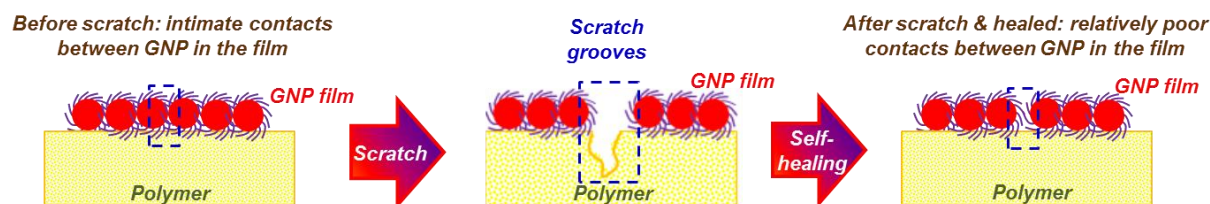
Figure S3. Schema of the contacts for GNP (in the film) before and after scratch. Subsequently, the contacts between GNP in the film became relatively poor, leading to the performance of the sensor being reduced to <100% after full healing.
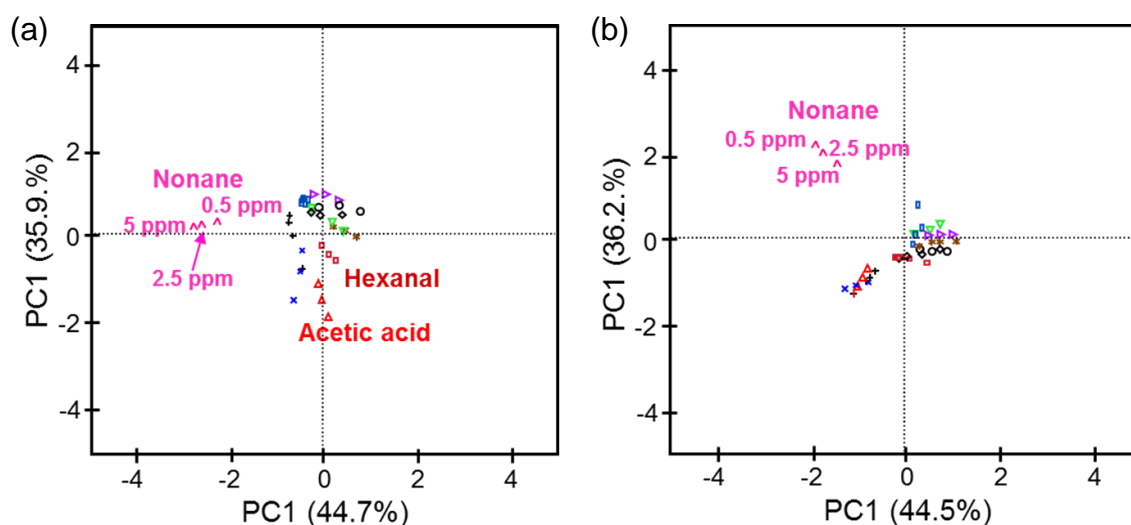
Figure S4. PCA schemes of the dataset for the sensor array in sensing of VOC in the range of 0.5-2.5 ppm: **(a)** after the second and **(b)** the third cycle of scratching/healing. After the second and third cycle of scratching/healing, the sensor array lost 73% of its original performance (3 VOCs can be discriminated) and 90% (only nonane could be discriminated) discrimination feature to the examined VOCs.

References:

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