

Stretchable Carbon Flower Sensors for Sensitive Estradiol Detection

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Summary:

Monitoring estradiol is crucial for female reproductive health, fertility, and hormone therapy, however existing sensor technologies often suffer from limited sensitivity and poor selectivity. Here, we present carbon flower sensors fabricated via a scalable spray-coating process on soft, stretchable substrates. The carbon flowers are obtained from polymerization of acrylonitrile followed by carbonization. They exhibit a hierarchical morphology, high surface area and excellent conductivity, enabling sub-nanomolar estradiol detection that exceeds state-of-the-art carbon-based sensors. The sensor operates under physiological conditions and demonstrates good repeatability. These results highlight the potential of carbon flower materials for sensitive estradiol detection and can be extended to other molecules such as ascorbic acid, melatonin, serotonin, and uric acid.

Keywords: estradiol sensing, stretchable sensors, electrochemical sensors, hierarchical carbon, spray coating

Background, Motivation and Objective

Estradiol plays an important role in female reproductive health and endocrine regulation. Real-time monitoring of estradiol levels is crucial for hormone replacement therapy, and disease management of endometriosis [1]. Conventional detection methods such as liquid chromatography-mass spectrometry provide high accuracy but require complex instrumentation and are not suitable for continuous monitoring. Electrochemical sensors offer portability, rapid detection, and compatibility with wearable devices. However, many sensing materials suffer from limited sensitivity, fouling, and selectivity in complex biological environments [2]. This work focuses on developing hierarchical carbon-based material for enhanced estradiol detection.

Description of the New Method or System

Hierarchical carbon flowers are a relatively new material studied in catalysis and supercapacitors [3] but remain largely unexplored for electrochemical sensing. They are synthesized via free radical polymerization of acrylonitrile precursors, followed by oxidative stabilization and

carbonization processes [4]. The resulting microstructures exhibit petal-like morphology (see Fig. 1a) with high surface area and conductive graphitic domains [5].

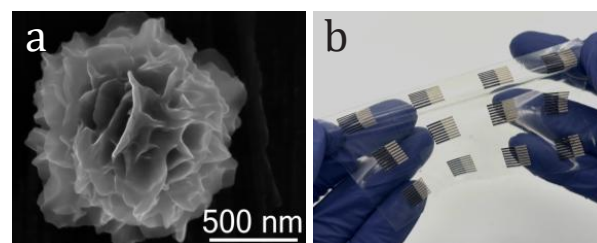


Fig. 1 (a) SEM image of carbon flower. (b) Photograph of stretchable sensor array.

The carbon flower material is dispersed into a printable ink and deposited onto flexible polystyrene-block-poly(ethylene-ran-butylene) block-polystyrene (SEBS) substrates using spray coating through metal masks [6]. This fabrication approach enables scalable patterning of stretchable sensor arrays (Fig.1b), offering advantages such as cost effectiveness and simple fabrication steps, without requiring expensive cleanroom facilities. The electrochemical performance for estradiol

detection is evaluated using square wave voltammetry (SWV), yielding concentration dependent current response.

Results

The electrochemical performance for estradiol detection is evaluated using SWV, which is shown in Fig. 2a. A pronounced oxidation peak appears at approximately 0.51 V and the current response increases for estradiol concentrations between 1 and 100 nM, exhibiting a linear dependence of peak current on estradiol concentration [5].

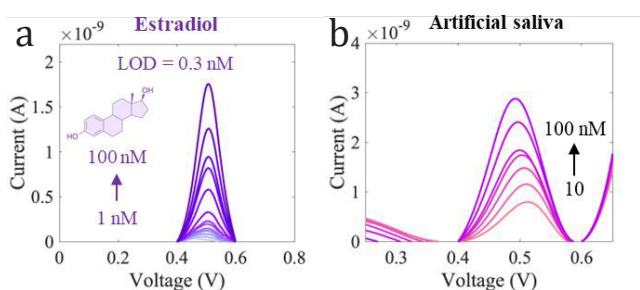


Fig. 2 (a) Detection of 1-100 nM estradiol via SWV. (b) Detection of 10-100 nM estradiol in artificial saliva.

The hierarchical carbon flower sensors achieve a limit of detection of 300 pM, outperforming state-of-the-art carbon-based sensors. We associate the improved sensitivity to the carbon flower morphology and the high surface area [6]. The sensors further demonstrate good stability during repetitive measurements, maintaining substantial responsiveness over 100 cycles. Robust performance is also observed under physiologically relevant conditions: within the saliva-relevant pH range, the peak position remains largely unchanged, while varying KCl concentrations up to 50 mM results in stable peak currents of 6.4 ± 0.5 nA [6]. Additionally, estradiol concentrations between 10 and 100 nM are successfully detected in artificial saliva (see Fig. 2b), confirming reliable sensing performance in complex media.

Conclusions

Carbon flowers are a promising material for electrochemical sensing. Using a simple spray

coating process, they can be patterned onto flexible substrates in a scalable and low-cost manner. Their unique hierarchical morphology and defect-rich structure lead to high surface area, enabling sensitive estradiol detection with a sub-nanomolar limit of detection. The sensors show good stability during repeated measurements and maintain reliable performance under physiologically relevant pH and salt conditions, as well as in artificial saliva. These results highlight carbon flowers as a practical and effective platform for stretchable and wearable sensors in sensitive electrochemical detection of estradiol, with potential extension to other molecules [6].

References

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