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Article

Preparation of a flexible glucose electrochemical sensor and its detection in elderly diabetic patients

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Abstract: The study proposes a diabetes detection scheme based on a novel flexible glucose electrochemical sensor for the current situation of diabetes management in China, especially for the elderly diabetic population. The sensor is fabricated using optimized conductive materials and diluents with set printing parameters. It mainly realizes non-invasive monitoring of human blood glucose by detecting human sweat, thus effectively detecting elderly diabetic patients. Simulation experiments showed that the sensor had a detection limit of 7.33 μM (S/N = 3) and a high sensitivity of 23.5 μA mm^{-2} for simulated sweat, demonstrating good stability and durability. Moreover, in the actual in vitro detection experiments, the sensor detected elderly diabetic patients with an accuracy of more than 98.3%. In addition, the response time of the sensor was very short, only 10.5 s to complete a detection, which was suitable for elderly patients. The above illustrated that the flexible glucose electrochemical sensor prepared in the research had certain feasibility and accuracy in the blood glucose monitoring of elderly diabetic patients. The research results not only provide theoretical basis and technical support for the preparation of flexible glucose electrochemical sensors, but also provide new ideas and methods for blood glucose monitoring and treatment of elderly diabetic patients.

Keywords: diabetes; sensors; glucose detection; elderly diabetics; physical characterization detection

1. Introduction

Diabetes mellitus, as a chronic metabolic disease, has become a major global public health challenge. Especially in the elderly population, the incidence of diabetes is high and often accompanied by multiple complications, seriously threatening the health and quality of life of the elderly. Accurate and ongoing blood glucose monitoring is essential for managing diabetes in older adults [1]. However, traditional methods of blood glucose testing mostly rely on invasive blood sampling, which not only causes inconvenience and pain to patients, but also limits the frequency and continuity of monitoring [2]. Therefore, the development of a noninvasive, real-time, and accurate blood glucose monitoring technique is important for improving disease management in elderly diabetic patients. Most of the traditional methods of blood glucose testing rely on invasive blood sampling, such as fingertip blood sampling, which not only causes physical inconvenience and pain to patients, but also limits the frequency and continuity of glucose monitoring. It is difficult to meet the needs of elderly diabetic patients for daily glucose management [3]. In addition, frequent blood collection operations may also increase the risk of infection, further aggravating the physical and mental burden of patients.

In recent years, scholars at home and abroad have made many advances in noninvasive glucose monitoring techniques, among which, electrochemical-based glucose sensors (GSs) have attracted much attention due to their high sensitivity and response speed [4]. Zafar et al. proposed a non-invasive continuous glucose monitoring scheme based on sweat sensors in response to the rising incidence of diabetes and the invasiveness and discontinuity of traditional glucose monitoring methods. The study outlined the state of the art, difficulties, and potential for future commercialization in this area by examining the latest developments in sweat glucose monitoring technology in recent years [5]. Saha et al. proposed a solution for non-invasive or minimally invasive body glucose monitoring using wearable electrochemical sensors in response to the increased demand for glucose monitoring devices due to the rising prevalence of diabetes. The study reviewed the electrochemical GS mechanism, sensor development history, and wearable glucose biosensor versions for different biofluids. The study revealed the current status and potential of wearable glucose biosensors [6]. Radhakrishnan et al. proposed the development of enzymatic and non-enzymatic GS using 2D materials to address the need for continuous glucose monitoring in diabetes management. This study reviewed the application of various 2D materials in GS and revealed the great potential of 2D materials in GS and their promise in realizing efficient, low-cost, and rapid glucose monitoring [7].

Based on the above studies, it is known that the existing electrochemical GSs need to be further strengthened in terms of detection accuracy and sensor stability, and the preparation process is relatively complicated. These problems limit the widespread application of noninvasive glucose monitoring technology, especially in the elderly diabetic population. In view of this, the study proposes a flexible glucose electrochemical sensor based on NiCo2O4 nanomaterials for detection. The sensor is prepared by using optimized conductive materials and diluents with precise printing parameters, and has good flexibility and biocompatibility, which enables it to fit the human skin for prolonged monitoring. The innovation of the study is that a flexible glucose electrochemical sensor based on NiCo2O4 nanomaterials is proposed, which can realize non-invasive, real-time, and accurate blood glucose monitoring for elderly diabetic patients.

2. Preparation of a flexible glucose electrochemical sensor and design of a method for detecting diabetes in the elderly

2.1. Sensor preparation materials and design

The flexible glucose electrochemical sensor combines electrochemical analysis with flexible materials technology and consists of a flexible substrate, a conductive layer and a sensing material that conforms to a variety of surfaces such as skin or clothing. Its flexible substrate makes it wearable and suitable for monitoring physiological parameters over long periods of time, making it suitable for health and exercise science applications. Flexible glucose electrochemical sensors enable real-time monitoring, increasing the frequency and accuracy of data collection. Moreover, it is easy to miniaturize and integrate into everyday wearable devices, enhancing

convenience and non-invasiveness. **Table 1** is a list of the tools and materials needed to prepare the instrument.

Table 1. List of experimental apparatus and experimental reagents.

Laboratory instruments	**Instrument model**	**Parameters**	**Production company**
Electrochemical workstation	CHI660E	Potential range ± 10 V, current range ± 250 mA	Shanghai Chenhua Instrument Co., Ltd, Shanghai, China
ICHY electrode adapter	ICHY-001	\	Beijing Centrwin Technology Co., Ltd, Beijing, China
Vacuum oven	DZF-6050	Temperature range: Room temperature ~250 ℃, vacuum degree < 133 Pa	Shanghai Yiheng Scientific Instrument Co., Ltd, Shanghai, China
Ultrasonic cleaning machine	KS-3000E	Power 300 W, frequency 40 kHz	Kunshan Shumei Ultrasonic Instrument Co., Ltd, Kunshan City, China
Ultra pure water machine	UPT-II-20L	Water production rate of 20 L/h, electrical resistivity ≥ 18.2M Ω·cm	Chengdu Youpu Ultra Pure Technology Co., Ltd, Chengdu, China
Centrifuge	SH2160R	The maximum speed is between 16,000–18,000 r/min	Shanghai Yiheng Scientific Instrument Co., Ltd, Shanghai, China
Multi functional microelectronic printer	MicroFlex	Printing accuracy is 5 μm	NanoInk Corporation, Skokie, IL, USA
High purity copper wire	Φ0.5 mm	Purity: 99.9%	Shanghai Nonferrous Metals Research Institute, Shanghai, China
Name	Production company	Name	Production company
Sodium hydroxide	Shandong LuKang Pharmaceutical Co., Ltd, Jining, China	L-ascorbic acid	Shanghai Yuanye Biotechnology Co., Ltd, Shanghai, China
		Uric acid	
Glucose		Arginine	
Thinner		Glycine	
PET substrate	Dongguan Zhicheng Fiber Materials Co., Ltd, Dongguan, China	L-phenylalanine	
Deionized water		L-glutamate	
CE600 conductive carbon paste	Shenzhen Jiayingfeng Technology Co., Ltd, Shenzhen, China	D-valine	
Base-CD01 silver paste		Dopamine hydrochloride	
Base-TFE01 encapsulated silicone		Folic acid	
01L-7211 silver chloride silver paste		Ascorbic acid	
\		Cysteine	

The selection and optimization of materials are key to ensuring superior performance in the fabrication process of flexible glucose electrochemical sensors. In **Table 1**, in terms of conductive materials, NiCo2O4 nanomaterials are selected due to their high electrocatalytic activity, large specific surface area (SSA), and good conductivity and stability, which can effectively catalyze glucose oxidation reactions and improve the sensitivity and response speed of sensors. Conductive carbon paste (CE600) is suitable for combination with flexible substrates and use in wearable devices due to its high conductivity, flexibility and biocompatibility. In terms of diluents, ethanol is suitable for uniform coating of materials due to its good solubility, volatility, and safety. Deionized water ensures accurate detection and is

suitable for large-scale production due to its high purity and environmental friendliness. In addition, PET substrates are suitable for long-term wear due to their flexibility, biocompatibility, and mechanical properties. The Nafion solution acts as a selectively permeable membrane to enhance the selectivity and stability of the sensor. The optimized combination of these materials ensures the reliability of the sensor in terms of sensitivity, response time and long-term use. The most important part of the flexible glucose electrochemical sensor is the chip module, which is the core model for detecting glucose. In **Figure 1**, the particular design is displayed.

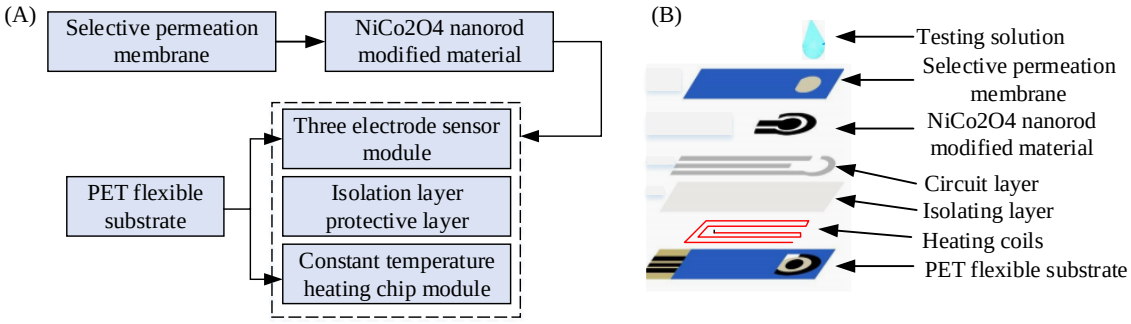

Figure 1. Design process and structural diagram of flexible glucose electrochemical sensor chip module. **(A)** Sensor chip design flowchart; **(B)** sensor assembly design diagram.

In **Figure 1**, the core component of the research-designed flexible glucose electrochemical sensor consists of five main parts. The first one is the flexible poly to polyethylene terephthalate (PET) substrate. PET is a polymer material with non-toxic, skin-friendly, hypoallergenic reactive properties and excellent mechanical properties [8]. The PET material ensures that it does not cause any irritation or allergic reaction to the user's skin during prolonged wear or use, thus significantly enhancing the safety and comfort of the product. The research-designed flexible glucose electrochemical sensor is fabricated on a PET substrate of 100 × 180 × 0.150 mm size. The circuit layer and heating coil of the sensor are then printed onto the PET substrate using microelectronic flexible printing technology. The circuit layer and heating coil are also separated by an isolation layer [9]. The isolation layer is made of polydimethylsiloxane, which has good flexibility and biocompatibility, and effectively separates the electrode layer from the heating layer as an isolation layer. It not only realizes the overheating protection of the electrode layer, but also ensures the safety of electrical isolation.

The working electrode of the three-electrode sensor is then evenly coated with the NiCo2O4 nanomodified material. The preparation method of NiCo2O4 nano modified material is shown in **Figure 2**.

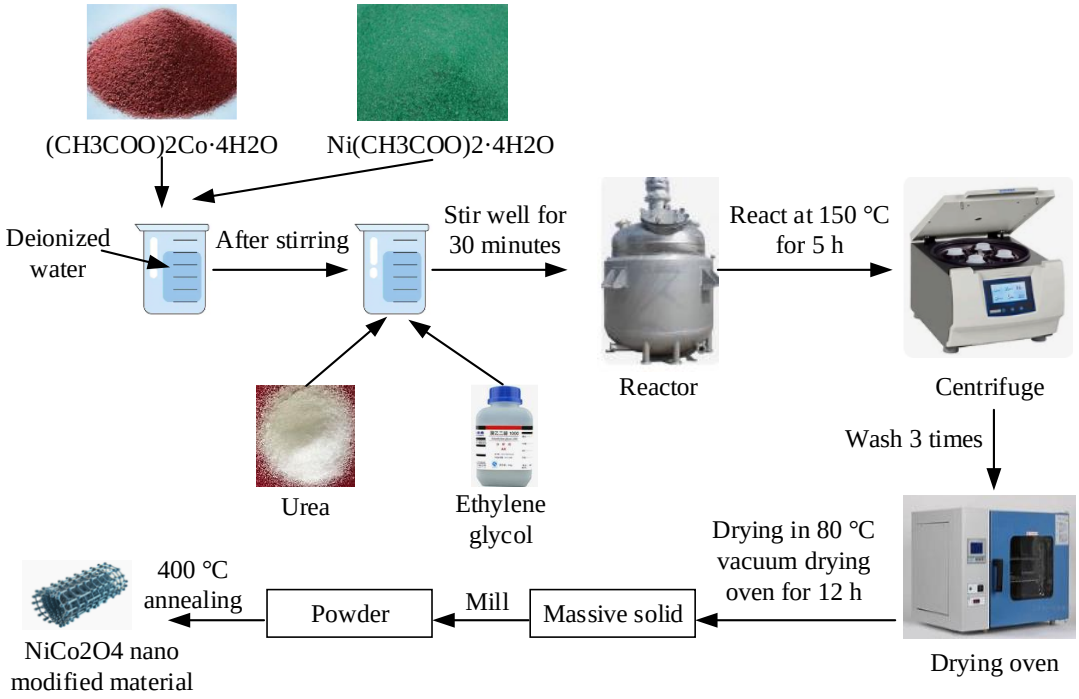

Figure 2. Preparation process of NiCo2O4 nano modified material.

In **Figure 2**, 124.54 mg (0.25 mmol) of cobalt acetate tetrahydrate (ATH) is placed in a beaker with 62.22 mg (0.125 mmol) of nickel ATH and dissolved in 5 mL of deionized water. Subsequently, 450.46 mg (0.25 mmol) of urea is added and mixed thoroughly. Afterwards, to guarantee uniform mixing, 10 mL of ethylene glycol is added to the mixture, and stirring is maintained for 30 min. The mixed solution is transferred to a 100 mL PTFE ceramic lined autoclave and reacted at 150 °C for 5 h. After the reaction is finished, the product is collected using an SH2160R bench-top high-speed centrifuge and cleaned three times each with ethanol and deionized water to get rid of any impurities and unreacted material. The washed samples are dried in a DZF-6050 vacuum drying oven at 80 °C for one day. After drying, the solid blocks are ground into powder. Next, the powder is burned in air at 400 °C for 3 h. Finally, NiCo2O4 nanocarbonized solid is obtained.

The glassy carbon bare electrode (GCE) is pretreated before modifying the electrode using NiCo2O4 nanocarbonized solid. It is polished sequentially using 1.0 μm, 0.3 μm, and 0.05 μm alumina polishing powders. Then, it is rinsed with deionized water and ethanol (1:1 v/v), ultrasonically cleaned and naturally dried. To prepare the modified electrodes, 2.5 mg of accurately weighed NiCo2O4 nanorods (NRs) material is uniformly dispersed into 500 μl of ethanol solution. Subsequently, this mixture is placed in an ultrasonic processor and treated with high-intensity ultrasound for 30 min. The cavitation effect of ultrasound can effectively break the agglomeration between the material particles and promote its uniform dispersion in the solvent, thus forming a fine and stable suspension of NiCo2O4NRs. The suspension of 2.5 μl is applied dropwise on the pretreated GCE, and the solvent is rapidly evaporated under infrared light to remove the excess material. To ensure uniform coverage, the drop coating is repeated once. The modified electrode is named NiCo2O4NRs-GCE. Once the coating is complete, it is allowed to dry naturally, followed by the addition and re-drying of a drop of Nafion solution on the

surface, which creates a strong, selectively permeable membrane. This film immobilizes the modifying material and also accurately screens the active glucose components in the solution to be tested to ensure that they are in full contact with the modifying material and react with it.

2.2. Material performance testing method for flexible glucose electrochemical sensors

The wide surface area, appropriate pore size and volume, and superior electrical conductivity (EC) of the NiCo2O4 nanomaterials generated for the study are responsible for the effective and quick selective detection of glucose using NiCo2O4 nanomaterial-modified glassy carbon electrodes. In a broad linear range, this allows NiCo2O4NRs-GCE to demonstrate good sensitivity and low detection limit [10,11]. To confirm the effectiveness of the sensor made using NiCo2O4NRs-GCE, the study plans related tests. The details are shown in **Figure 3**.

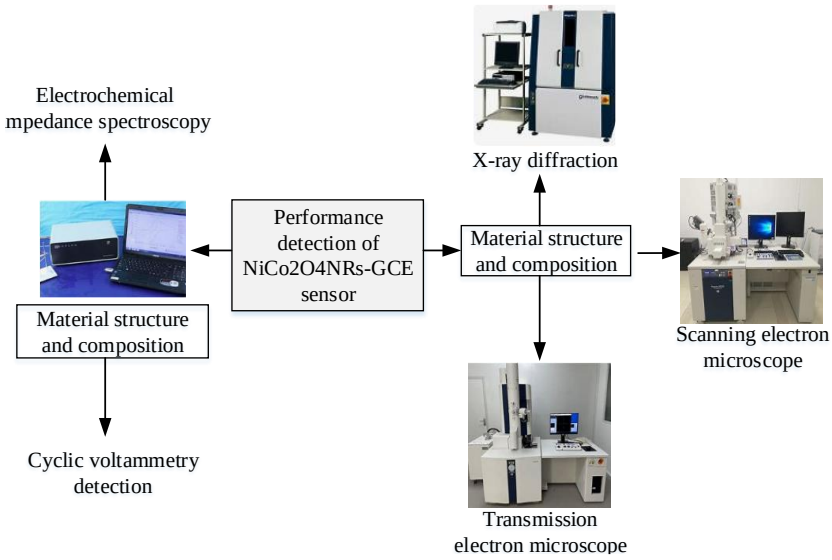

Figure 3. Performance testing scheme for NiCo2O4NRs GCE prepared sensor.

In **Figure 3**. The material structure and composition analysis experiments are mainly divided into three inspection methods: X-ray diffraction, scanning electron microscope (SEM), and transmission electron microscope (TEM).

1) X-ray diffraction: The NiCo2O4 nanomaterial sample is first refined to powder form by grinding. Then, the NiCo2O4 powder sample is fixed on the sample holder using a special sample holder, making sure that the sample is centered and parallel to the holder surface. An Empyrean model X-ray diffractometer from Malvern Panaco is selected for detection. The Ni target is selected as the radiation source and the X-ray wavelength is set to 1.5406 Å. With a step size of 0.01° and a scanning speed of 5°/min, the XRD diffraction angle 2θ is configured to range between 10° and 80°. The voltage of the X-ray tube is adjusted to 110 kV and the current to 50 mA. After setting up the above measurement conditions on the software interface, the instrument starts to send X-rays and record the diffraction signals. After waiting for the scanning to be completed, the diffraction data are exported and subsequently analyzed.

2) SEM: The NiCo2O4 nanomaterial samples are dried and agglomerates are removed, and the samples are homogeneously dispersed in ethanol solvent. The processed samples are mounted onto the sample stage of the SEM. The accelerating voltage of the instrument is set to 4 KV, the working distance is 1 mm, and the electron beam current is 100 pA. The SEM is activated, and the characteristics of NiCo2O4 nanomaterials in terms of particle size, shape, distribution, and surface morphology are observed and recorded [12].
3) TEM: NiCo2O4 nanomaterial samples are dispersed in ethanol solvent and the dispersion is sonicated using an ultrasonic processor to further disperse the nanoparticles. The dispersion is added dropwise onto a special TEM sample carbon film, and the sample is formed after the solvent evaporates. The prepared TEM sample is mounted onto the sample stage of the TEM. The TEM is activated to observe and record the lattice structure, particle size, shape, internal defects, and other characteristics of NiCo2O4 nanomaterials [13].

Electrochemical behavioral experiments include electrochemical impedance spectroscopy, cyclic voltammetry detection.

1) Electrochemical impedance spectroscopy: The prepared NiCo2O4NRs-GCE sensor is put into the CHI660E electrochemical workstation. The frequency range of the electrochemical workstation is set to 2 Hz–10 Hz, the amplitude is 10 mV, and the number of sampling points is 100. The electrochemical workstation is started and the test begins. During the test, the electrochemical workstation will automatically generate a sinusoidal disturbance signal and measure the response signal (RS). Meanwhile, the experimental data, comprising the phase angle and other information, as well as the real and imaginary sections of the impedance, will be recorded by the data acquisition system [14].
2) Cyclic voltammetry detection: The working electrode, reference electrode, and counter electrode are connected to the electrochemical workstation. On the electrochemical workstation, the cyclic voltammetry parameters are set at −0.4 V for the start potential, 0.6 V for the termination potential, 150 mV/s for the scan rate, 50 for the cycle number, and 0.02 s for the sampling interval. The electrochemical workstation is started to begin cyclic voltammetry testing [15].

2.3. Sensor detection of elderly diabetes program

After passing the performance test, the qualified flexible glucose electrochemical sensor is used for elderly diabetes detection. The overall scheme of flexible glucose electrochemical sensor for detection of elderly diabetes is shown in **Figure 4**.

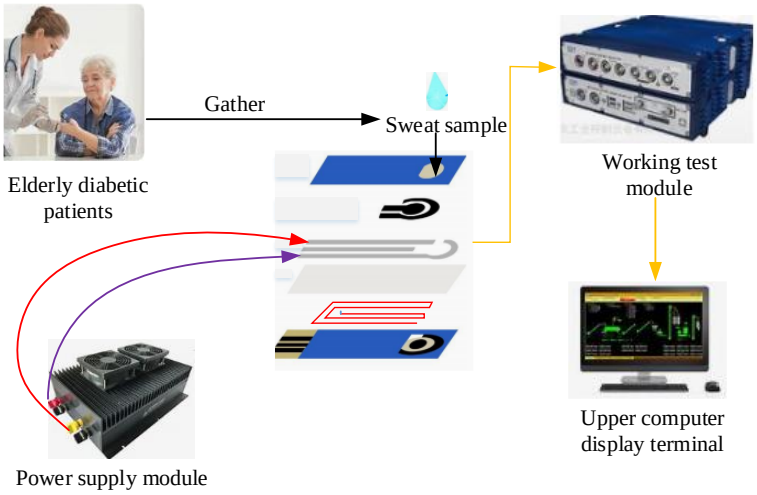

Figure 4. Flow of flexible glucose electrochemical sensor to detect elderly diabetes.

In **Figure 4**, sweat samples from older people can be obtained non-invasively by attaching the sensor to the patient's skin or clothing such that it is in complete contact with the perspiration. The patient's sweat sample will permeate the NiCo2O4 nanomaterials through the Nafion selective permeable membrane, and the RS of the sensor will be recorded by the detection equipment of the electrochemical workstation module, and the RS of the sensor will be displayed on the display side of the upper computer. Based on the current RS of the sensor, the glucose concentration (GC) in the sample can be calculated. The detected GC is compared with the normal blood glucose range to determine whether the patient is in a hyperglycemic state. Meanwhile, the doctor will combine the patient's other clinical information, such as age, gender, and medical history, to conduct a comprehensive analysis and provide personalized diagnosis and treatment recommendations for the patient.

3. Sensor material properties and geriatric diabetes detection results

3.1. Physical characterization test results of sensor preparation materials

The physical microscopic morphology and structural details of NiCo2O4 nanomaterials are first observed using SEM and high resolution TEM. **Figure 5** displays the findings.

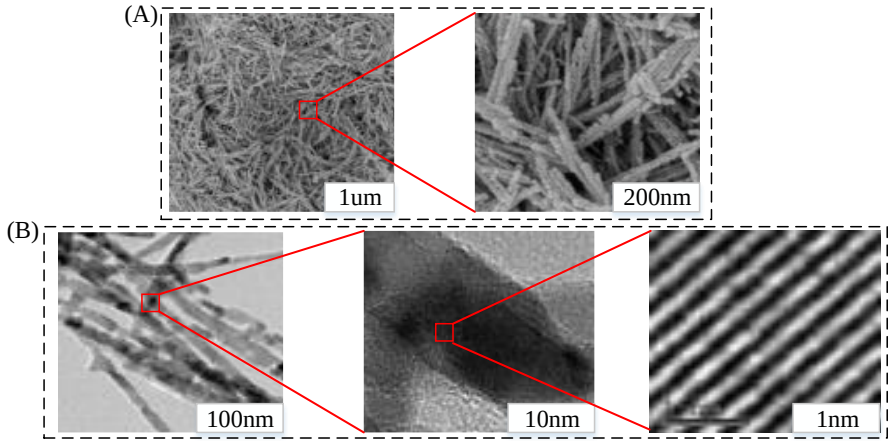

Figure 5. SEM and high-resolution TEM images of NiCo2O4 nanomaterials. **(A)** SEM image; **(B)** SEM image.

Figure 5A shows the SEM image of NiCo2O4 nanomaterials. The NiCo2O4 nanomaterials show a uniformly dispersed state with no obvious agglomeration or aggregation. The NiCo2O4 nanomaterials are in rod-like morphology with an average diameter of about 9 nm and an average length of about 350 nm. Because a larger SSA can provide more active sites, the rod-like shape and size distribution of NiCo2O4 nanoparticles aid in improving their effectiveness in catalytic processes. **Figure 5B** displays the high resolution TEM image of NiCo2O4 nanomaterials. The NiCo2O4 nanomaterials have good crystallinity and structural stability. The internal metal active sites are well dispersed, which facilitates the effective utilization of the active sites in the catalytic reaction, thus enhancing the catalytic performance of the NiCo2O4 nanomaterials. Then the X-ray diffraction test of NiCo2O4NRs is carried out using Empyrean model X-ray diffractometer, while the X-ray diffraction results of NiCo2O4NRs are refined by Rietveld using GSAS software. The results are shown in **Figure 6**.

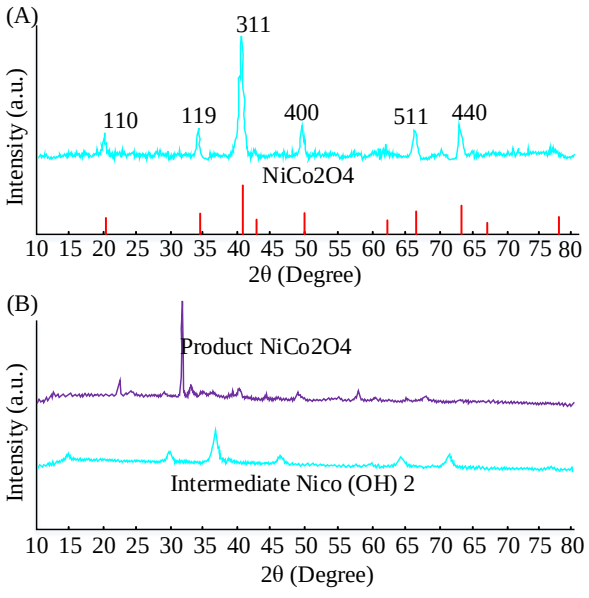

Figure 6. XRD pattern of NiCo2O4 NRs. **(A)** Standard XRD spectra of NiCo2O4 NRS; **(B)** XRD spectra of intermediates and products of NiCo2O4 NRS.

Figure 6A shows the standard XRD pattern of NiCo2O4 NRs, which are the diffraction peaks observed at 2θ values of 31.3°, 36.8°, 40.16°, 44.7°, 59.3°, and 66.1°, respectively. These respective diffraction peaks correspond to (110), (119), (311), (400), (511), and (440) crystal reflections of NiCo2O4, indicating that the investigated prepared NiCo2O4 NRs are successfully synthesized. It also indicates that the studied prepared materials have good crystallinity and expected crystal structure. **Figure 6B** shows the intermediate and product maps of NiCo2O4 NRs. In addition to the characteristic diffraction peaks of NiCo2O4, some additional diffraction peaks can be observed, which correspond to the diffraction peaks of the hydroxide phases Ni(OH)2 (00 + 059 + 0463) and Co(OH)2 (00 + 002 + 1094). The presence of these hydroxide phase peaks reveals that the precursor material is not completely converted to NiCo2O4 during the synthesis process, but there are some residual intermediate phase hydroxides. However, the intensity of these residual intermediate phase peaks is not high enough to affect the properties of the prepared materials.

3.2. Sensor electrochemical behavior detection results

Electrochemical impedance test is performed on the NiCo2O4 NRs sensors prepared for the study using CHI660E electrochemical workstation. Blank and NiCo(OH)2 sensors are also selected for comparison. **Figure 7** displays the findings.

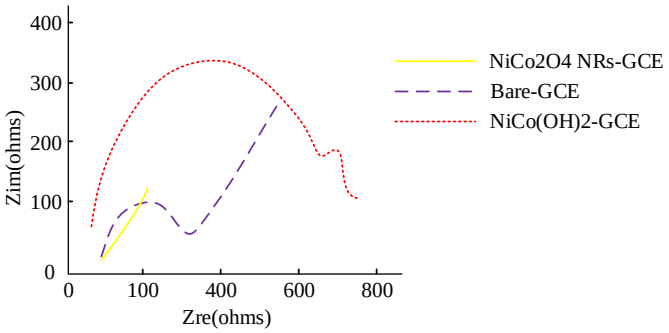

Figure 7. Electrochemical impedance test results of three types of sensors.

In **Figure 7**, comparing the electrochemical impedance of the blank electrode, NiCo2O4 NRs-GCENi/Co(OH)2-GCE in a specific solution, the NiCo(OH)2 material modified electrode has poor conductivity and low charge transfer efficiency. In contrast, the NiCo2O4 NRs-GCE prepared by the study exhibits the lowest charge transfer resistance (about 50 Ω) and the best electrocatalytic activity to facilitate the electron transfer process of the sensor. The electrochemical performance of these three electrodes for glucose oxidation is then tested by cyclic voltammetry. **Figure 8** displays the findings.

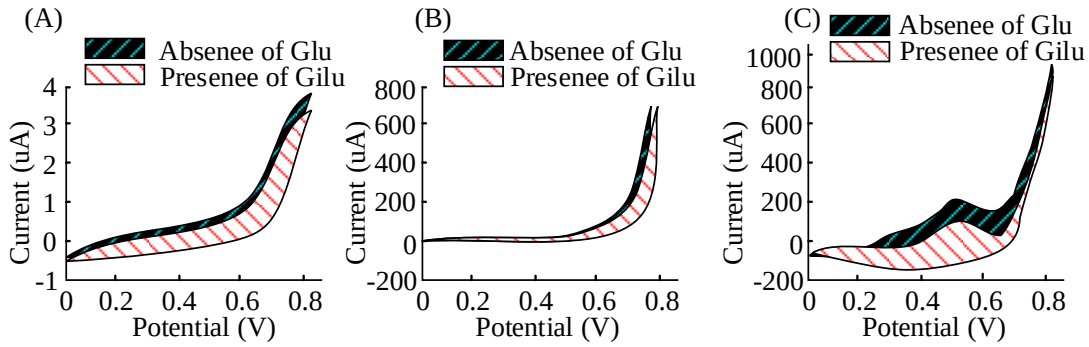

Figure 8. Shows the electrochemical performance test results of three electrodes for glucose oxidation. **(A)** The electrochemical performance of Bare GCE on glucose oxidation; **(B)** electrochemical properties of NiCo (OH) 2-GCE for glucose oxidation; **(C)** electrochemical properties of NiCo2O4 NRs GCE for glucose oxidation.

In **Figure 8**, the responses of the blank electrode, Ni/Co(OH)2-modified electrode and NiCo2O4 nanomaterial-modified electrode to glucose in NaOH solution are compared. The weak catalytic effect of the blank electrode on glucose indicates its slow electron transfer kinetics. The glucose oxidation current of the Ni/Co(OH)2-modified electrode is significantly enhanced due to the additional electroactive sites provided by Ni and Co ions. In contrast, the NiCo2O4 NRs-GCE prepared in the study exhibits more excellent catalytic performance with a more pronounced increase in oxidation current, which is attributed to the excellent electrocatalytic properties, good EC, and large SSA of the NiCo2O4 material. It also indicates that the human glucose content can be effectively detected based on NiCo2O4 NRs-GCE.

3.3. Analysis of sensor biocompatibility testing results

To verify the biocompatibility of the sensor materials. The study first conducts cytotoxicity experiments by culturing human skin HFF-1 cells, soaking the sensor material in cell culture medium, and preparing material extraction solution. The cells are separately exposed to material extract and normal culture medium (control group) and cultured for 24 h. MTT assay is used to detect cell viability and calculate cell survival rate. The results shows that the cell survival rate of the material extraction solution group should be > 90%, indicating that the sensor material has no significant cytotoxicity.

Next, a skin irritation test is conducted using monkeys to simulate human skin contact, and the sensor material is applied to the back skin of the monkeys for 24 h. Skin tissues are taken for pathological sections to observe any inflammatory cell infiltration or tissue damage. The results shows that the monkeys had no irritating reactions, and there should be no significant inflammation or damage to the skin tissue.

3.4. Analysis of elderly diabetes test results

The NiCo2O4 NRs-GCE, reference electrode, and auxiliary electrode are inserted into a beaker containing 0.1 mol/L NaOH solution, and a magnetic stirrer is used to keep the solution uniformly stirred. The parameters of the chrono-current method are set on the electrochemical workstation, and the initial current value is

recorded by first performing a baseline test with 0.55 V as the operating voltage. Using a microsyringe, glucose standard solutions of different concentrations are injected continuously into the solution at 30 s intervals. The current response is recorded after each injection until a steady state current is reached. **Figure 9** displays the findings.

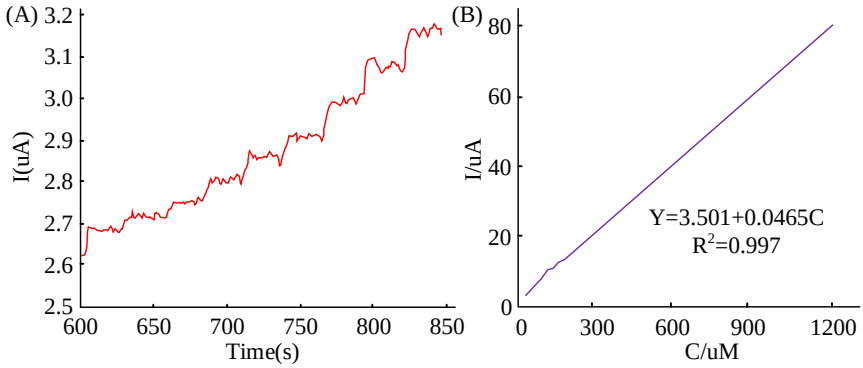

Figure 9. Shows the corresponding calibration curve between current signal and GC. **(A)** Typical I-t curve of NiCo2O4 NRS GCE; **(B)** current signal and GC diagram.

In **Figure 9**, the NiCo2O4 NRs electrochemical sensor performs well in glucose detection. The sensor responds rapidly and sensitively to glucose, and can reach a steady-state current response within 5.5 s. Its current response exhibits a good linear relationship with GC. According to the linear regression equation, in the range of 1.4 μM-1165.8 μM, the investigationally prepared sensor has a high sensitivity of 23.5 μA mm^{-2} and a low detection limit of 7.33 μM (S/N = 3). This is mainly due to the high SSA and suitable pore size of NiCo2O4 nanomaterials, these properties accelerate the charge transfer process and thus improve the performance of the sensor. The study utilizes the sensor to test 1000 elderly diabetic patients. To evaluate the selectivity of flexible glucose electrochemical sensors for interfering substances such as ascorbic acid, uric acid, and lactic acid, simulated sweat (PBS buffer) is used as the base solution. Moreover, 0.1 mM glucose, 0.1 mM ascorbic acid, 0.1 mM uric acid, and 0.1 mM lactic acid are added to the base solution. The sensor is then fixed on the simulated sweat surface for testing. The results are shown in **Figure 10**.

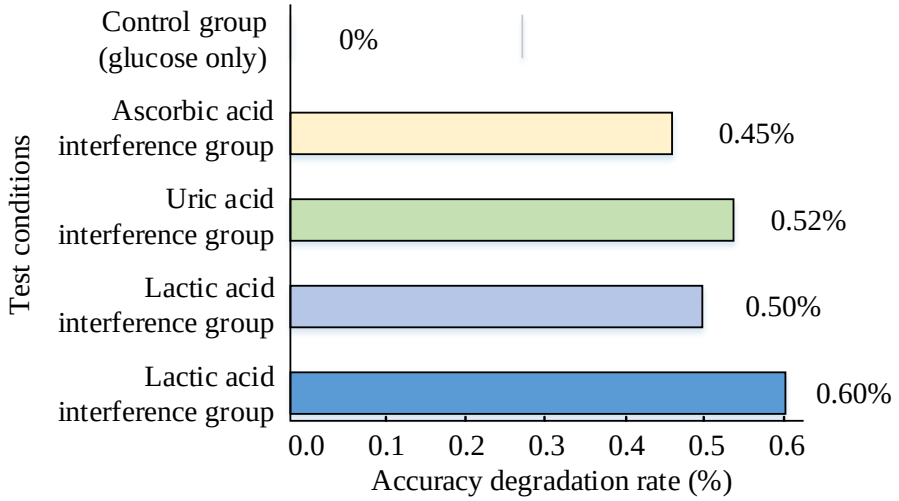

Figure 10. Decrease rate of detection accuracy of flexible glucose electrochemical sensor under different interference conditions.

In **Figure 10**, the presence of interfering substances can lead to a decline in the sensor's detection accuracy of up to 0.8%, suggesting that its accuracy in detecting glucose is relatively resilient to interference. This property renders the sensor suitable for actual diabetes patient detection. The sensor is used to detect 1000 elderly patients with diabetes. The statistical table of 1000 elderly patients with diabetes is shown in **Table 2**.

Table 2. Statistical table of 1000 elderly patients with diabetes.

Characteristic	**Classification/Scope**	**Sample size (n = 1000)**
Age stratification	60–70 years old	400
	71–80 years old	450
	Over 80 years old	150
Type of diabetes	type 1 diabetes	50
	type 2 diabetes	950
Course of disease	< 5 years	300
	5–10 years	400
	> 10 years	300
Complication	Cardiovascular disease	400
	Kidney disease	250
	Retinopathy	200
	No complications	150
Skin thickness	Thinner (< 1.5 mm)	300
	Medium (1.5–2.5 mm)	500
	Thicker (> 2.5 mm)	200
Sweat volume	Low sweat volume	400
	Moderate sweat volume	450
	High sweat volume	150

Real sweat samples are collected from these elderly diabetic patients and venous blood samples are collected from the patients as a clinical gold standard. Sweat samples are directly measured using a flexible electrochemical GS, while venous blood samples are measured for GC using a standard blood glucose meter. The results of the sensor are compared with the results of the venous blood glucose test as shown in **Table 3**.

Table 3. Comparison between sensor detection results and venous blood glucose detection results.

Sample number	Sensor detection result (mmol/L)	Venous blood glucose test results (mmol/L)	Deviation (mmol/L)	Correlation coefficient
1	7.5	7.6	+0.1	
2	8.0	8.1	+0.1	
3	9.1	9.0	−0.1	
4	7.0	7.0	0.0	0.95
5	6.9	6.8	−0.1	
…	…	…	…	
1000	7.6	7.6	0.0	

In **Table 3**, the correlation coefficient between the sensor detection results and the venous blood glucose detection results is 0.95, with a maximum deviation of ± 0.1. It indicates a high consistency between the sensor detection results and the gold standard. Comparative experiments are also conducted with common glucose oxidase sensors, non-invasive GS, and metallic material GS. **Figure 11** presents the findings.

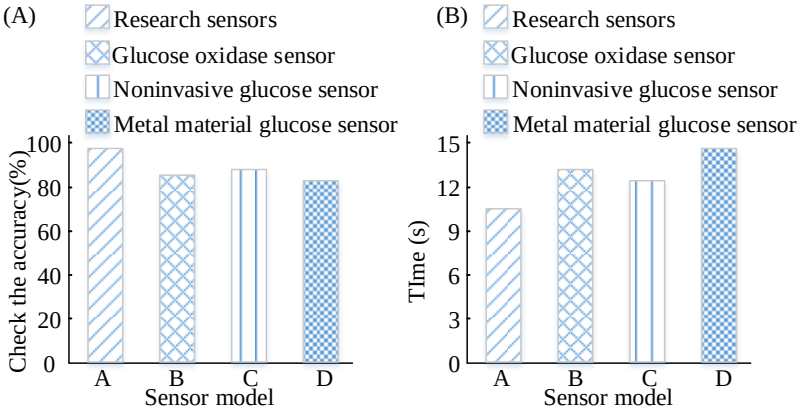

Figure 11. Sensor detection accuracy and detection time. **(A)** Check the accuracy; **(B)** check the time.

In **Figure 11A**, the sensor detects elderly diabetic patients with an accuracy of more than 98.3% in an actual in vitro detection experiment, which is higher than other common elderly diabetes sensors. In **Figure 11B**, the response time of the sensor is very short, only in 10.5 s to complete a detection, which is suitable for elderly patients. The study is to evaluate the performance stability of flexible electrochemical GSs in long-term use, including changes in key indicators such as sensitivity, response time and detection accuracy. The study also tests the above 1000 elderly diabetes patients once a week for 28 days. Compared with the

traditional fingertip blood glucose meter, continuous blood glucose monitoring system and non-invasive blood glucose monitoring technology in the existing diabetes monitoring technology, the results are shown in **Table 4**.

Table 4. Stability evaluation test results of blood glucose detection methods.

Flexible glucose electrochemical sensor						
Test days	**Sensitivity (μ A/mM)**	**Sensitivity attenuation rate (%)**	**Average response time (s)**	**Response time increase rate (%)**	**Detection accuracy (%)**	**Accuracy degradation rate (%)**
Day 1	23.5	0%	10.5	0%	98.3	0%
Day 7	23.2	1.3%	10.6	1.0%	98.0	0.3%
Day 14	22.8	3.0%	10.8	2.9%	97.8	0.5%
Day 21	22.5	4.3%	11.0	4.8%	97.5	0.8%
Day 28	22.0	6.4%	11.2	6.7%	97.2	1.1%
Traditional fingertip blood glucose meter						
Day 1	22.96	0%	10.7	0%	90.1%	0%
Day 28	18.35	20.08%	11.4	6.89%	82.3%	8.66%
Continuous glucose monitoring system						
Day 1	20.96	0%	10.1	0%	90.4%	0%
Day 28	18.65	11.02%	10.9	7.92%	85.3	5.64%
Non invasive blood glucose monitoring technology						
Day 1	21.63	0%	11.6	0%	86.4%	0%
Day 28	17.85	17.48%	12.4	6.90%	81.4%	5.79%

As shown in **Table 4**, the flexible electrochemical GS exhibits excellent performance stability during the 30-day test period. At day 30, its sensitivity decreased by only 6.4%, the average response time increased by only 6.7%, and the detection accuracy decreased by only 1.1%. In contrast, conventional fingertip glucose meters experience a significant decrease in sensitivity of 20.08%, a significant increase in response time of 6.89%, and a significant decrease in accuracy of 8.66% within 30 days. The sensitivity of the continuous glucose monitoring system decreased by 11.02%, the response time increased by 7.92%, and the accuracy decreased by 5.64%. The sensitivity of the noninvasive glucose monitoring technology decreased by 17.48%, the response time increased by 6.90%, and the accuracy decreased by 5.79%. The findings indicate that the flexible glucose electrochemical sensor exhibits superior performance in terms of long-term stability, particularly with regard to maintaining sensitivity and accuracy, when compared to the other three monitoring technologies. This renders it highly suitable for patients requiring prolonged blood glucose monitoring. The traditional fingertip blood glucose meter technology is mature and widely used, but it requires frequent blood sampling, which undoubtedly brings many inconveniences and pains to patients. The continuous glucose monitoring system can monitor blood glucose changes in real time and provide patients with continuous blood glucose data. However, it is expensive, inconvenient to wear, and requires regular replacement of sensors. There may also be problems such as signal interference and errors. The non-invasive blood glucose monitoring technology does not require blood sampling, which greatly

reduces patients' pain, but its accuracy still needs to be further improved, and the price is relatively high. The accuracy of the flexible electrochemical GS designed in this study in the detection of elderly diabetes patients is as high as 98.3%, which is far higher than the traditional fingertip blood glucose meter and some non-invasive blood glucose monitoring technologies. In addition, the sensor can complete a detection in only 10.5 s, which is not only faster than other popular diabetes sensors for the elderly, but also comparable to some fingertip glucose meters. This rapid detection capability helps elderly patients obtain timely blood glucose information, enabling them to make appropriate adjustments and treatments quickly.

4. Conclusion

Aiming at the current situation of geriatric diabetes management in China, the study proposed a flexible glucose electrochemical sensor based on NiCo2O4 nanomaterials for detection. The sensor was prepared by precise printing parameters using optimized conductive materials and diluents, and is capable of non-invasive monitoring of blood glucose by detecting human sweat. The NiCo2O4 nanomaterials displayed a homogenous dispersion and rod-like morphology with an average diameter of around 9 nm and an average length of approximately 350 nm following physical characterisation detection and electrochemical behavior investigation. In the analysis of electrochemical behavioral detection results, NiCo2O4 NRs-GCE exhibited the lowest charge transfer resistance and the best electrocatalytic activity, which could significantly facilitate the electron transfer process of the sensor. These properties enabled the sensor to perform well in glucose detection with fast response, high sensitivity, and good linearity. In practical applications, the sensor could detect elderly diabetic patients with an accuracy of more than 98.3% and an extremely short response time of only 10.5 s for a single detection. The results illustrated that the sensor had the ability of non-invasive, real-time and accurate blood glucose monitoring, which not only provided a more reliable means of disease management for elderly diabetic patients, but also provided a more accurate diagnostic basis for medical personnel. However, other components in human sweat may interfere with the performance of the sensor, resulting in measurement errors. Subsequent studies will further optimize the design of the sensor and improve its anti-interference ability to ensure accuracy and reliability in clinical applications.

Conflict of interest: The authors declare no conflict of interest.

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