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A portable, low-cost lactate measurement system

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Abstract: Lactate, as a metabolite, plays a significant role in a number of fields, including medical diagnostics, exercise physiology and food science. Traditional methods for lactate measurement often involve expensive and cumbersome instrumentation. This study developed a portable and low-cost lactate measurement system, including independently detectable hardware circuits and user-friendly embedded software, computer, and smartphone applications. The experiment verified that the relative error of the detection current in the device circuit was less than 1%. The electrochemical performance was measured by comparing the $[Fe(CN)_6]^{3-}/[Fe(CN)_6]^{4-}$ solution with the desktop electrochemical workstation CHI660E, and a nearly consistent chronoamperometry (CA) curve was obtained. Two modified lactate sensors were used for CA testing of lactate. Within the concentration range of 0.1 $mmol\cdot L^{-1}$ to 20 $mmol\cdot L^{-1}$, there was a good linear relationship between lactate concentration and steady-state current, with a correlation coefficient (R^2) greater than 0.99 and good repeatability, demonstrating the reliability of the developed device. The lactate measurement system developed in this study not only provides excellent detection performance and reliability, but also achieves portability and low cost, providing a new solution for lactate measurement.

Key words: lactate measurement; portable device; embedded development; lactate sensor; electrochemical analysis

0 Introduction

In recent years, lactate, a metabolic product of glycolysis, has gained recognition for its significant role across various biomedical fields, including exercise physiology, drug evaluation, and food science. Therefore, the demand for accurate determination of lactate concentrations has been heightened, especially in disease monitoring and exercise performance evaluation[1]. Accurately measuring lactate levels is crucial for assessing disease severity and metabolic status post-surgery. For example, in athletes, it aids in evaluating vivo energy metabolism and training fatigue[2]; in food science, lactate serves as a pivotal indicator of fermented foods, correlating directly with fermentation progression and final product quality. Therefore, developing a portable and low-cost lactate measurement system has important practical value.

Advancements in lactate measurement methods have integrated various detection techniques into clinical and sports medicine, significantly improving the efficiency and accuracy of lactate measurements. Conventional methods primarily rely on laboratory analyses, typically involving arterial blood samples[3] through techniques such as high-performance liquid chromatography (HPLC) and enzymatic methods. While these methods are known for their high accuracy and reliability, particularly in critically ill patients, they have the drawback of prolonged turnaround time, often several hours, which may not be ideal for emergency and rapid diagnoses[4]. With technological advancements, handheld lactate analyzers, such as lactate pro and lactate plus, have been gradually introduced into clinical environments. These devices provide rapid lactate measurements from small blood samples, making them suitable for both clinical and sports settings[5]. They yield results within minutes and are user-friendly, which enhances their applicability in emergency treatment and sports monitoring. However, differences in equipment accuracy and operator skill levels lead to potential errors in results[6]. Recently, point-of-care testing (POCT) has emerged as a detection method that allows real-time lactate measurement at the patient's bedside, significantly reducing the time required to obtain results. Studies have shown that using bedside POCT for lactate measurement can expedite patient treatment and improve nursing efficiency[7]. Although the accuracy of this method is slightly lower than that of laboratory analysis, its speed and convenience have made it increasingly popular for clinical applications. Furthermore, the advent of microneedle technology has opened new avenues for lactate monitoring. This technology allows for continuous and pain-free measurement of lactate concentration in interstitial fluid. The noninvasive and continuous monitoring capabilities make it ideal for long-term observation and early detection, providing dynamic data that can assist healthcare providers in adjusting treatment plans promptly[8,9]. However, current technologies are still in development and may face challenges regarding stability and accuracy[10].

In recent years, with the development of mobile terminal technology[11,12], researchers have begun to explore how to improve the portability and ease of operation of electrochemical detection instruments. By combining high-sensitivity electrochemical biosensors with small devices based on mobile terminals and utilizing the computing and display functions of mobile phones, a good alternative solution for biochemical detection has been developed[13-15], which also provides a research background for the development of portable lactate detection instruments in this study. For example, CheapStat developed by Rowe et al. [16] meets the needs of educational resource limited environments with low cost and ease of assembly. The DStat developed by Dryden et al.[17] is capable of precise electrochemical measurements, with open-source and portable features, and can be easily integrated into other instruments. Subsequent studies such as KAUSTat[18], MiniStat[19] and KickStat[20] have made progress in portability and miniaturization design, and have achieved wireless connectivity with smartphones or PCs through Bluetooth, WiFi, and RF transmission. Nanostat[21] and FreiStat[22] demonstrate the potential of wireless and IoT technologies in electrochemical analysis, further advancing the design of embedded potentiometers. Although these designs have made breakthroughs in functionality and performance, there are still some limitations. For example, many embedded potentiometers based on smartphones or computers have complex designs, high costs, strong dependence on external devices, and are difficult to flexibly use in different situations, which limits the wide applications of the equipment. Therefore, developing a portable, reliable, and low-cost lactate measuring instrument with simple design and strong flexibility is of great significance[23].

In this study, a portable, low-cost, high-performance lactate measurement system that supports multiple detection methods is developed. The device is equipped with buttons and a display screen, which can independently complete measurements, and can also be connected to a computer or smartphone via Bluetooth for real-time monitoring of lactate. In addition, the total design cost of the device is less than \$15. The independently detectable circuit design of the device is simple, with stable and reliable performance. The reliability of the electrochemical performance of the device was verified through the $[Fe(CN)_6]^{3-}/[Fe(CN)_6]^{4-}$ model, and the repeatability was good. In the lactate measurement experiment, the results of combining two lactate sensors showed that the system exhibited a good linear relationship in the concentration range of 0.1 $mmol \cdot L^{-1}$ to 20 $mmol \cdot L^{-1}$. The comparison results show that the enzymatic lactate sensor (ELS) has a better response effect, but its stability is relatively poor and the cost is high; In contrast, the nonenzymatic lactate sensor (NLS) not only has low cost and high stability, but also has a simple modification process and higher cost-effectiveness. The portable lactate measurement system proposed in this study, combined with three-electrode electrochemical sensing technology, can be applied in fields such as sports medicine and food quality monitoring, and has important practical value.

1 Materials and methods

1.1 Experimental reagents and instruments

Electrochemical workstation CHI660E (Shanghai Chenhua Instrument Co., Ltd.); Lactate oxidase (LOx), $FeCl_3$, H_2SO_4, Chitosan, PBS, CH_3COOH, KCl/HCl, Carbon Nanotubes (CNT), NaOH, $K_4Fe(CN)_6$, KCl, and $C_3H_6O_3$ were purchased from Sinopharm Chemical Reagent Co., Ltd. NiO was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd, and 5 wt% of Nafion was purchased from Sigma-Aldrich. all the reagents were analytically pure, and the water used in the experiments was deionised water. The screen-printed electrodes used included a C-working electrode, a C-counter electrode, and an Ag/AgCl reference electrode.

1.2 Lactate sensor preparation

1.2.1 ELS

Mix 0.1 g chitosan with 10 mL of 2% CH_3COOH and stir magnetically for 1 h. Add 2 mg of CNT to 1 mL of 1% Chitosan solution and sonicate for 1 h. Mix the Chitosan-CNT solution with an equal volume of LOx solution and sonicate for 30 min. Add 30 μL of 0.1 M H_2SO_4 dropwise onto the electrode surface, perform 10 cycles of cyclic voltammetry scanning, repeat 2—3 times to remove impurities and activate the electrode.

Add 30 μL of mixed solution to the electrode, dry it, then add 2.5 μL of 5% Nafion solution dropwise and dry it again. Store the ELS[24,25] in a fridge at 4 ℃.

1.2.2 NLS

Mix 20 mg NiO powder with 100 μL Nafion and 1 mL ethanol, stir at high speed for 1 h, and sonicate for 1 h. Add 8 μL of NiO/Nafion suspension drop wise to the electrode and dry at 25 ℃ for 2 h. The NLS[26] was prepared by performing cyclic voltammetry scan ($50\ \mathrm{mV \cdot s^{-1}}$) in $0.1\ \mathrm{mmol \cdot L^{-1}}$ NaOH solution until a stable cyclic voltammetry curve was obtained.

1.3 Design of lactate measurement system

The overall structure of the lactate measurement system mainly consists of three parts: power management module, signal acquisition and processing, and human-computer interaction display. The working diagram is shown in Fig.1.

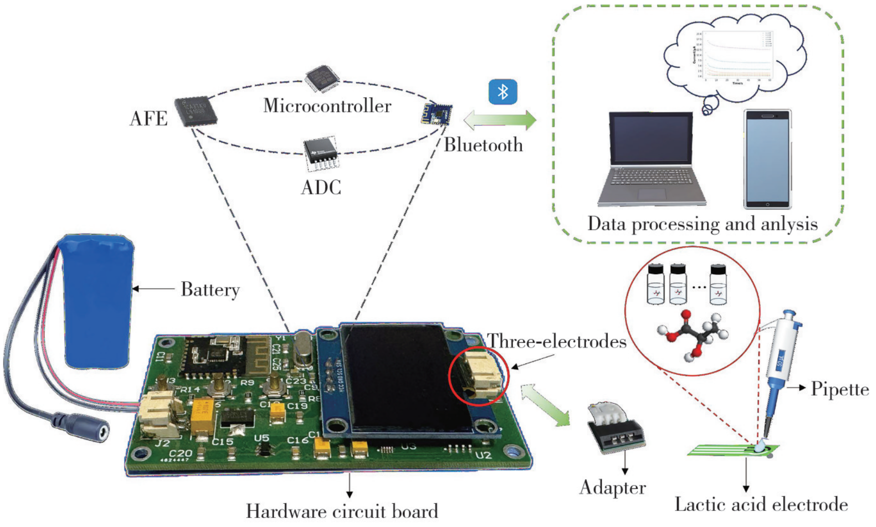
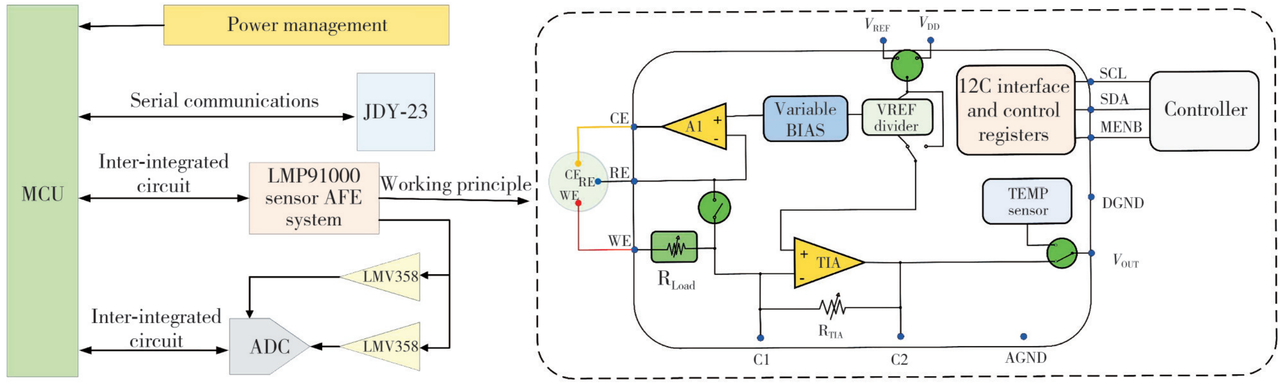


Fig. 1 Schematic diagram of lactate measurement system

1.3.1 Hardware design

The hardware design of the lactate detection system adopts a modular approach, with a circuit board size of <31.8 cm^2, mainly including a main control chip, an analog front-end (AFE), a microcurrent detection module, a battery management module, and a display module.

The structure is shown in Fig.2.



(a) Schematic diagram (b) AFE working principle diagram

Fig. 2 Hardware design of lactate measurement system

The AFE is the core of the entire instrument, enabling timely and accurate detection of the current generated by electrochemical reactions. This module uses the LMP91000 chip to amplify the current, with a working voltage range of 2.7 V to 5.25 V. The bias voltage and transimpedance amplifier gain can be adjusted through I^{2}C to control the constant potential value and the output range of the I-V converted voltage signal. The working principle is shown in Fig.2(b). The V_{REF} voltage divider and variable bias are divided from the external reference voltage to provide potential for RE, and the internal zero position voltage is the positive phase voltage of TIA. The variable bias circuit provides the voltage difference required for WE to operate, and selects the bias polarity and bias voltage value through I^{2}C programming. In order to maintain a constant potential difference between WE and RE, any impedance changes between WE and RE will be counteracted to CE through operational amplifier A1, forming a constant potential circuit. A flexible external gain resistor can be connected between C1 and C2, with a maximum allowable gain resistor of 350 kΩ. Based on the detectable range of lactate concentration, the optimal voltage output range is selected for the signal acquisition circuit and the V_{C1} potential is set to 67% of V_{REF}.

The microcurrent acquisition module processes and converts the voltage signal detected by the AFE into a digital signal for the MCU to read. The module consists of a low-pass filtering circuit and an ADC. In order to improve the quality of the signal, a second-order low-pass filtering circuit is set up before the ADC collects the signal to filter out the interference of the power frequency signal. ADC adopts differential input method, which reduces the error when switching R_{TIA} and improves the accuracy of current measurement compared to traditional single ended measurement method. The single ended measurement is calculated by

$$I_{OUT}=(V_{OUT}-V_{REF}\times 67\%)/R_{TIA}, \tag{1}$$

and the differential input is calculated by

$$I_{OUT}=(V_{OUT}-V_{C1})/R_{TIA}. \tag{2}$$

As shown in Fig.5, the battery management module has upgraded the power adapter power supply scheme previously studied[27] to lithium battery power supply. In order to ensure the stable output of the lithium battery and the overall performance of the system, a +5 V power supply is connected through J2 port, and the +5 V voltage is converted into a 3.3 V power supply through TI's low voltage regulator AS1117, providing a stable working voltage of 3.3 V to STM32f103C8T6, bluetooth, and ADC. To eliminate the interference of noise and oscillation caused by the +5 V power supply to LMP91000, an efficient linear regulator MIC5205-5.0 is used to provide stable +5 V operating voltage and input voltage for LMP91000.

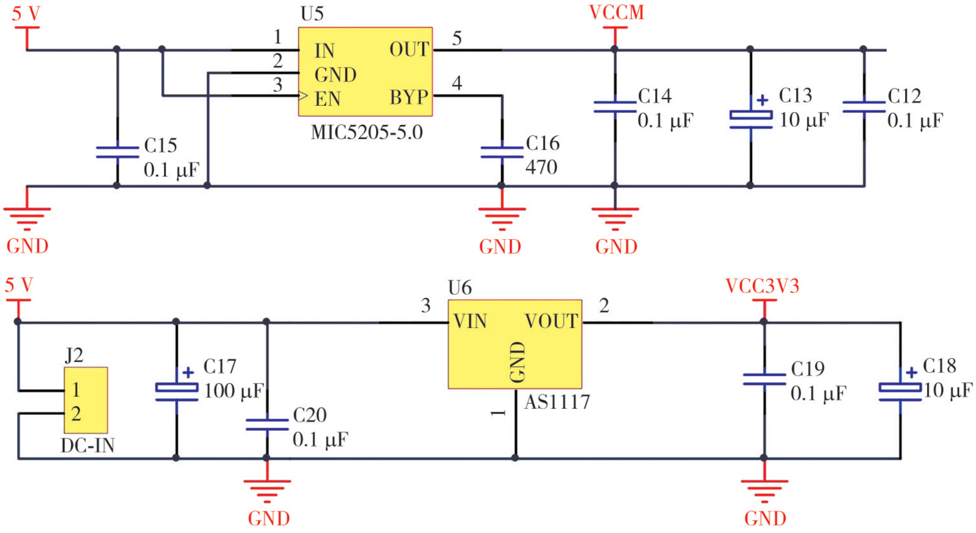


Fig. 3 Voltage stabilization circuit

The display module integrates a built-in display screen and physical buttons, allowing users to directly view and operate the instrument without relying on external devices, enhancing the flexibility and user friendliness of the instrument. The interface circuit is shown in Fig.4.

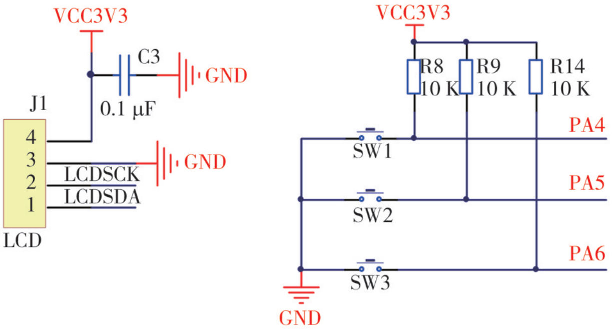


Fig. 4 Button and LCD interface circuit

1.3.2 Software design

The software design of the lactate measurement system adopts an integrated strategy to ensure the functionality of the instrument and the portability of user interaction. The core of the software lies in its data processing algorithm, which first cleans the data received through the Modbus serial port, and then removes spaces, ensuringg the accuracy of the data. Next, the cleaned data are parsed and converted from the hexadecimal format data substring into current values.

This process involves extracting specific parts (the 7th to the 10th characters) from the data, converting them into hexadecimal integers, and calculating the current value (I) through the scaling factor (fRadio). The software periodically receives, parses, and processes data through a timer event handler, while controlling the timer logic to execute tasks at specific time intervals and calculate steady-state current values when preset conditions are met. The calculation of steady-state current is completed by taking the average of the last 10 data points to ensure the stability and accuracy of the output results. The software design process is shown in Fig.5.

Embedded software is responsible for direct interaction with hardware, including data acquisition, signal processing, preliminary analysis, and display of key parameters such as lactate concentration in real time through an embedded display screen. The design of the display screen focuses on intuitiveness, allowing users to quickly obtain measurement results through a simple user interface. In order to improve user experience and data processing capabilities, smartphone and computer applications have been developed to communicate with the lower computer via bluetooth. The smartphone application is programmed in Java language and a connection is established with the bluetooth module of the lower computer through the bluetooth API of android. It uses Modbus RTU protocol to communicate with the hardware system and obtain experimental data in real time. The software allows users to perform real-time monitoring of data using the timed current method and save the data. The computer application is programmed in C# language and is connected to the JDY-23 bluetooth chip through built-in bluetooth to achieve data transmission. The interface design is simple, allowing users to view lactate standard curves, real-time current values, and lactate concentration data. The software interface is shown in Fig.6.

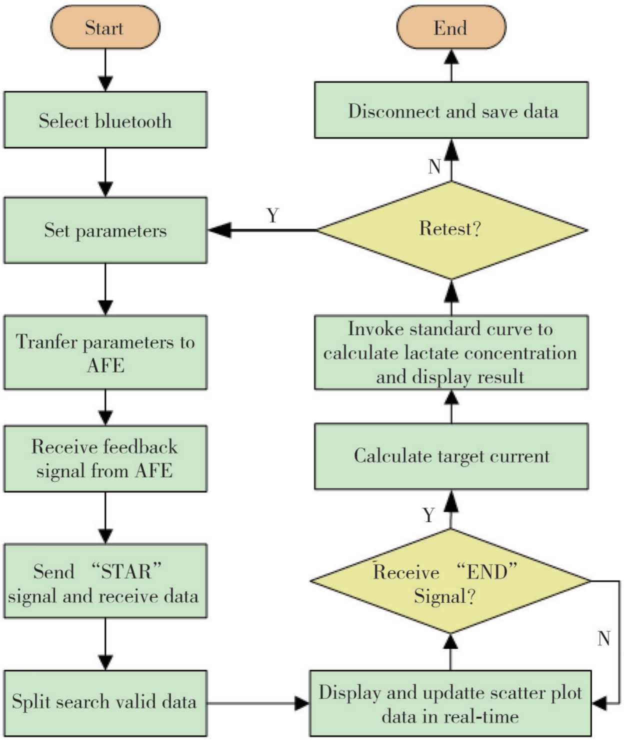
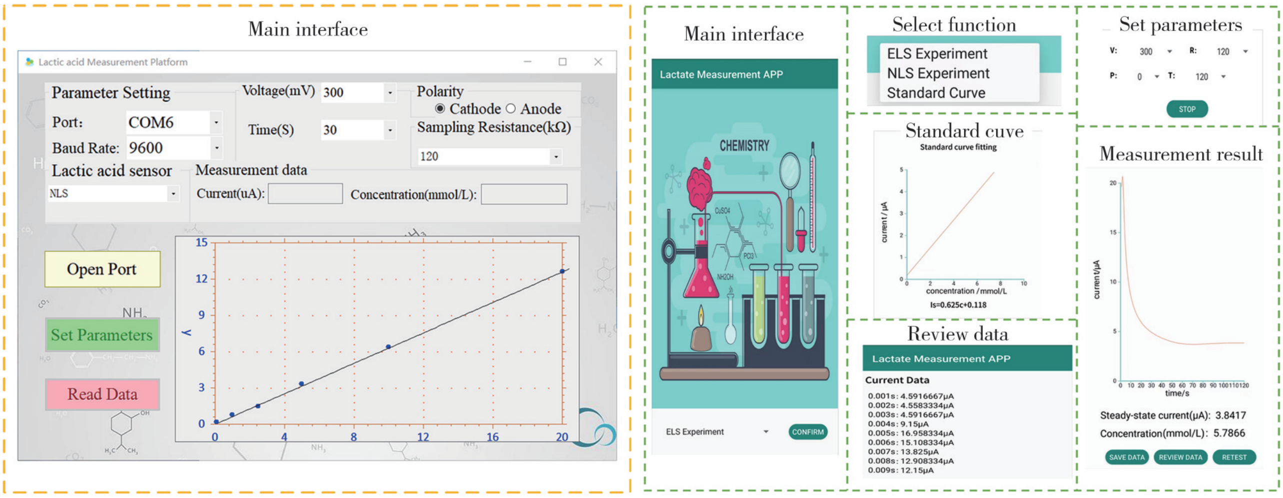


Fig. 5 Flow chart of software design



Parameter Setting
Port: COM6
Baud Rate: 9600
Voltage(mV): 300
Time(S): 30
Polarity ● Cathode ○ Anode
Sampling Resistance(kΩ): 120
Lactic acid sensor: NLS
Measurement data
Current(uA):
Concentration(mmol/L):

V: 300 R: 120
P: 0 T: 120

Lactate Measurement APP
Current Data
0.001s: 4.5916667μA
0.002s: 4.5583334μA
0.003s: 4.5916667μA
0.004s: 9.15μA
0.005s: 16.958334μA
0.006s: 15.108334μA
0.007s: 13.825μA
0.008s: 12.908334μA
0.009s: 12.15μA

Steady-state current(μA): 3.8417
Concentration(mmol/L): 5.7866

(a) Computer application (b) Smartphone application

Fig. 6 Software interface design

2 Results and discussion

2.1 System performance test

2.1.1 Circuit detection accuracy test

According to the basic principle of the three-electrode system and its applicability to DC signals, the reaction electrolysis cell can be equivalent to the simplified equivalent model[28,29] of the three-electrode electrochemical sensor shown in Fig. 7, where R_S and R_{FW} are the resistance of the solution between the counter electrode (CE), reference electrode (RE), and working electrode (WE). Connecting the multimeter in series to the circuit, the current (I_w) flowing through the working electrode satisfies $I_w = V_{RW}/R_{FW}$, where V_{RW} is the potential difference between RE and WE. According to the model, parameter measurements are performed. From Fig. 8, it can be seen that the measured current value decreases with the increase of resistance and increases linearly with the increase of set voltage. The correlation coefficient (R^2) is greater than 0.97, which is consistent with the theoretical situation. The relative error between actual current and theoretical current is below 1%, meaning that the developed instrument can ensure good detection accuracy.

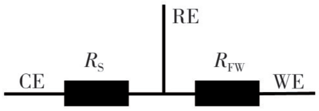


Fig. 7 Simplified equivalent model of three-electrode electrochemical sensor

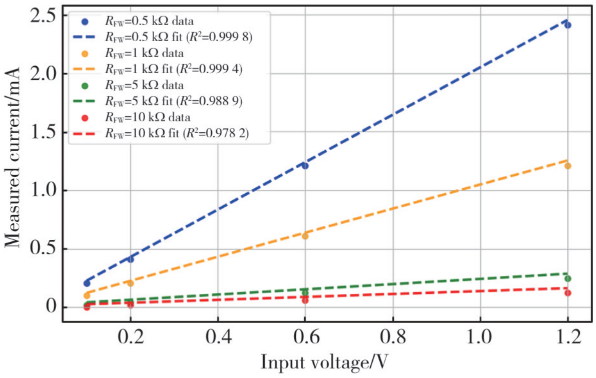
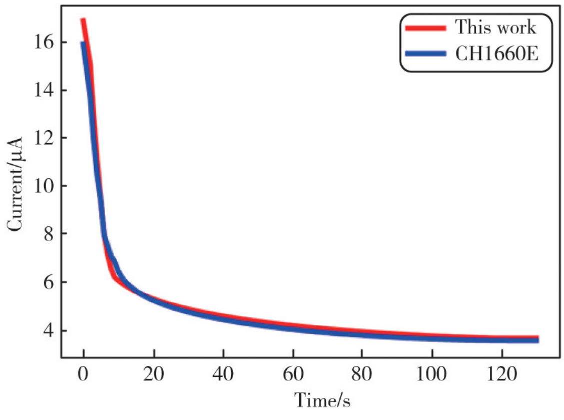


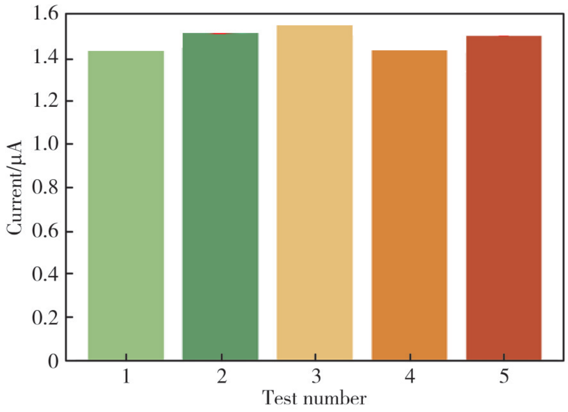
Fig. 8 Actual current measured under different resistances and set voltages

2.1.2 Electrochemical performance test

To evaluate the electrochemical performance of this device[30,31], a chronoamperometry (CA) experiment was conducted in a 5 mmol·L^{-1} [Fe(CN)$_6$]$^{3-}$/[Fe(CN)$_6$]$^{4-}$ solution at a voltage of 0.3 V for 2 min. The detection results are compared with the desktop electrochemical workstation CHI660E, as shown in Fig.9, and the timing current curve is highly coincident.



(a)



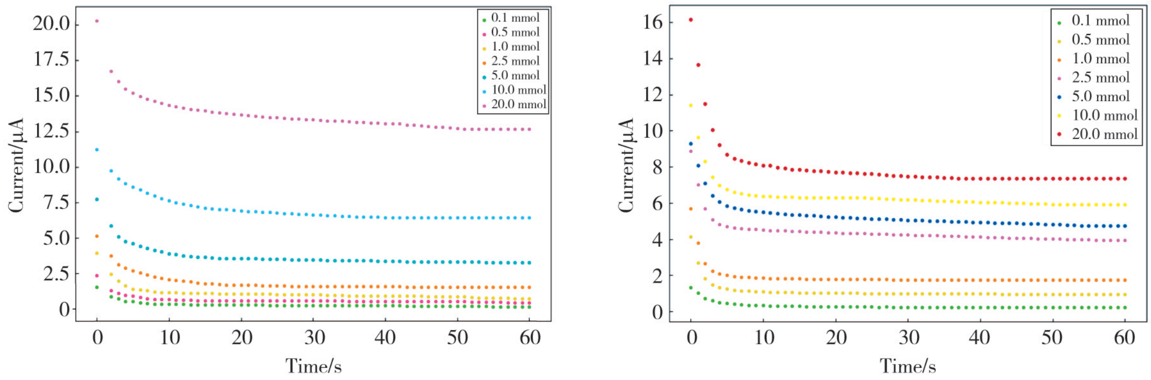
(b)

Fig. 9 Electrochemical performance test results. (a) comparison of timing current curves between this instrument and CHI660E, and (b) comparison of steady-state current heights of five repeated experiments

In addition, in the above experimental environment, five CA experiments were conducted on a 2 mmol·L^{-1} [Fe(CN)$_6$]$^{3-}$/[Fe(CN)$_6$]$^{4-}$ solution to verify the repeatability of the instrument (see Fig.9). The standard deviation of steady-state current was 0.047 μA, and the coefficient of variation was 3.18%.

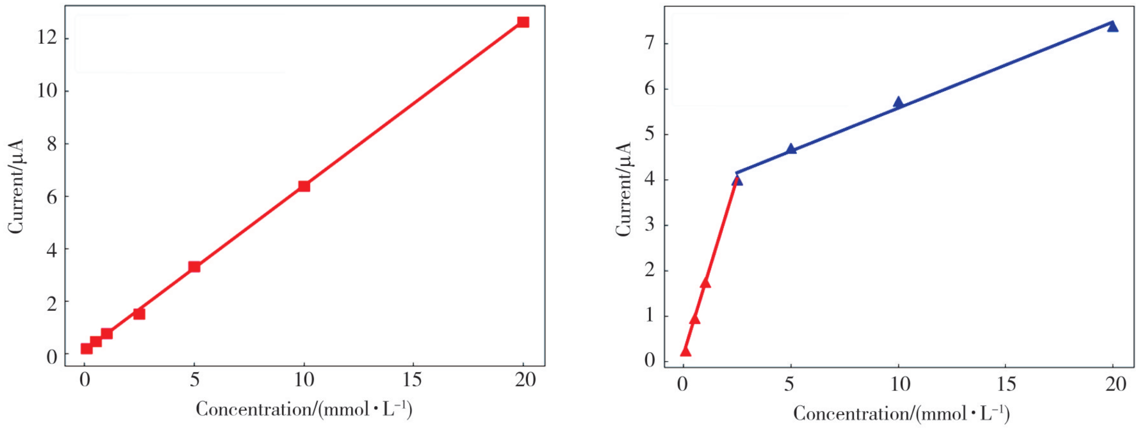
2.2 Lactate measurement

In order to verify the accuracy and stability of the device in detecting lactate, CA tests were conducted on lactate solutions with different concentrations. The experiment used a series of diluted lactate standard solutions with concentrations ranging from 0.1 mmol·L^{-1} to 20 mmol·L^{-1} to simulate the lactate levels in actual samples. Five independent measurements were taken for each concentration sample to ensure data reproducibility and reliability. The experimental potential was 0.3 V for 60 s, and two types of lactate sensors were used for lactate measurement experiments. As shown in Fig.10, within the range of 0.1 mmol·L^{-1} to 20 mmol·L^{-1}, the steady-state current value gradually increases with the increase of lactate concentration. The linear equation is $I_{ELS(0.1-20\ mmol/L)}=0.625C+0.118$ (R^2=0.999, with a sensitivity of 0.625 μA/(mmol·L^{-1}·cm^2), the limit of detection (S/N=3) was 0.017 mmol·L^{-1}); and $I_{NLS(0.1-2.5\ mmol/L)}=1.549C+0.15$, $I_{NLS(2.5-20\ mmol/L)}=0.189C+3.681$ (R^2=0.998 and 0.991, with a sensitivity of 1.549 μA/(mmol·L^{-1}·cm^2), the limit of detection (S/N=3) was 0.005 mmol·L^{-1}). The coefficient of variation of ELS experiment is less than 12.04%, and the coefficient of variation of NLS experiment is less than 2.46%. The comparison of measurement data from two types of electrodes shows that the ELS sensor has a better response to lactate, but its stability is poor and the cost is high. In contrast, NLS sensors not only have simple modification, low cost, and high stability, but are also less susceptible to environmental influences, making them more cost-effective.



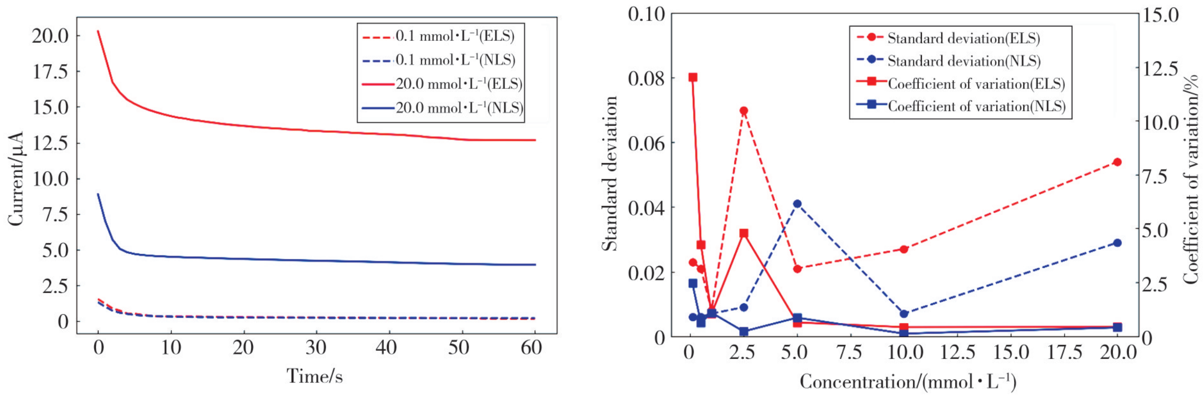
(a) ELS lactate measurement timing current curve

(b) NLS lactate measurement timing current curve



(c) Linear relationship between ELS steady-state current and lactate concentration

(d) linear relationship between NLS steady-state current and lactate concentration



(e) Comparison of timing current response of two electrodes to lactate at concentrations of 0.1 mmol·L^{-1} and 20 mmol·L^{-1}

(f) Comparison of standard deviation and coefficient of variation of measurement data from two electrodes in five repeated experiments

Fig. 10 Analysis of lactate measurement results

The results of the instrument test are consistent with Ref.[32], proving the reliability of the instrument for measuring lactate and adapting it to common three-electrode lactate sensors.

2.3 Comparison with existing solutions

As shown in Table. 1, the device allows a maximum current of 882 μA, ensuring its wide applicability. Wireless connection is achieved via bluetooth, and the device supports multiple detection methods. Powered by lithium batteries, compared to power adapters, the device has enhanced its wireless function, improves its portability, and facilitated on-site testing in different locations. In addition, the design cost of the entire device, including the battery, circuit, and electrodes, is less than $15. The lactate measurement system developed has low cost and high performance compared to current portable devices, and provides better portability.

Table 1 Comparison between this work and previously developed portable detection devices

Device	Power souce	Max current/μA	Data output	Data processing	Cost/$
Cheapstat[16]	USB	50	USB	Computer	80
DStat[17]	USB	—	USB	Computer	120
KAUSTat[18]	Battery	100	Bluetooth	Smartphone	—
MiniStat[19]	Battery	100	USART	Computer	20
NanoStat[21]	Battery	582	WiFi/Internet	Computer /Smartphone	25
FreiStat[22]	Battery/USB	900	WiFi/Cloud	Computer	86.7
This study	Battery	882	Bluetooth	Computer /Smartphone/Stand-alone	15

3 Conclusions

This paper presents a small lactate measurement system based on an electrochemical three-electrode system, which has the advantages of portability, low cost, stable performance, and multiple detection methods. The test on ircuit detection accuracy showed that the relative error of the current was less than 1%, and the detection accuracy reached microampere level. Through CA experiments on $[Fe(CN)_6]^{3-}/[Fe(CN)_6]^{4-}$, compared with the electrochemical workstation CHI660E, almost identical timing current curves were obtained, and the coefficient of variation in the repeatability experiment was 3.18%, verifying the reliability of the system. Two modified lactate sensors were used for CA testing of lactate, and both showed good linear relationships ($R^2>0.99$) in the concentration range of 0.1 $\text{mmol}\cdot\text{L}^{-1}$ — 20 $\text{mmol}\cdot\text{L}^{-1}$, indicating that the instrument is suitable for common three-electrode lactate sensors. The comparison results of two lactate sensors analyzed by the instrument showed that ELS had better response to lactate than NLS, but the cost was high and unstable, and NLS had a higher comprehensive cost-effectiveness. Compared with traditional lactate measurement methods, this system not only has simple operation and high flexibility, but also has low cost, providing a new method for rapid measurement of lactate. Our research findings are not limited to the current design. Future researchers can further innovate and improve this circuit, thereby expanding its potential applications in other fields.

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Declaration of conflicting interests

The authors have no conflict of interests related to this publication.

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一种便携、低成本乳酸测量系统

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摘　要：乳酸作为代谢产物，在医学诊断、运动生理学和食品科学等领域扮演重要角色。传统的乳酸检测技术通常配备昂贵且笨重的仪器。为此，开发了一种便携式、低成本的乳酸测量系统，包括可独立检测的硬件电路和用户友好的嵌入式软件、电脑及手机应用程序。实验验证了该装置电路的检测电流相对误差小于1%，电化学性能通过对$[Fe(CN)_6]^{3-}/[Fe(CN)_6]^{4-}$溶液的测量，与台式电化学工作站CHI660E进行比较，得到了近乎一致的计时安培电流法（Chronoamperometry，CA）曲线。使用修饰的两种乳酸传感器：乳酸酶传感器（Enzymatic lactate sensor，ELS）和非酶乳酸传感器（Nonenzymatic lactate sensor，NLS）对乳酸进行CA测试，在0.1－20 $mmol \cdot L^{-1}$的浓度范围内，乳酸浓度与稳态电流均呈现良好的线性关系，相关系数（R^2）大于0.99，且重复性良好，体现了所研制装置的可靠性。本研究开发的乳酸测量系统在提供优异的检测性能和可靠性的同时，实现了便携性和低成本，为乳酸测量提供了一种新的解决方法。

关键词：乳酸测量；便携式设备；嵌入式开发；乳酸传感器；电化学分析

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