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Development of Wearable Lactate Sensors with Dynamic Visual Pattern Responses

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Summary:
This study explored the responses of cotton fabrics functionalized with lactateresponsive and non-responsive polymers, focusing on color and pattern changes. Facial pattern samples were created using two monomer solutions and stained with anionic dyes. When immersed in 100 mM lactate, smiling faces gradually turned into crying faces. Pattern changes correlated with lactate concentration and response time, with full transformation observed after 120 min at 100 mM lactate. These findings suggest dye desorption from responsive areas enables visual, concentration-dependent lactate sensing.

Keywords: lactate, colorimetric, pattern change, boronic acid, smart textile

Introduction

Since lactate is a substance that serves as an indicator of physical fatigue and exercise intensity, easy measurement of lactate concentration in body fluids would be useful for not only top athletes but also for the general public to improve their competitive performance and health. Conventional lactate measurement methods require blood sampling, which imposes a heavy workload on athletes and related personnel (trainers and coaches), and does not allow continuous measurement, so improvements are needed. In recent years, methods for measuring lactic acid in sweat using wearable sensors have been developed. However, there are still many problems to be overcome, such as the large measuring device that interferes with the wearer's movement and the high cost and instability of the device.

In our laboratory, we are developing sportswears that changes its design in response to lactate using boronic acid as a lactate interface. Boronic acids are known to reversibly form negatively-charged complexes with *cis*-diol compounds such as saccharides. It is also known that boronic acids can interact with *α*-hydroxy acids in which a hydroxyl group binds to the *α*-carbon adjacent to the carboxyl group. By utilizing the characteristics of boronic acid, our group have succeeded in developing thin films that exhibit colorful responses against lactic acid. In the present study, we combined the above–mentioned lactic acid-responsive thin film with cotton fabric to develop sports wears that change their patterns in response to the lactic acid concentration in sweat. This is a completely different approach from conventional methods using enzymatic or electrochemical reactions. The wearer does not have to bear any extra burden such as sensing units and data transmitters, and the design changes in response to the lactate concentration in sweat simply by wearing the garment (Fig. 1). If such a wearable sensor that doesn't feel like wearing at all is put to practical use, it will enable anyone to easily determine the degree of physical fatigue and exercise intensity.

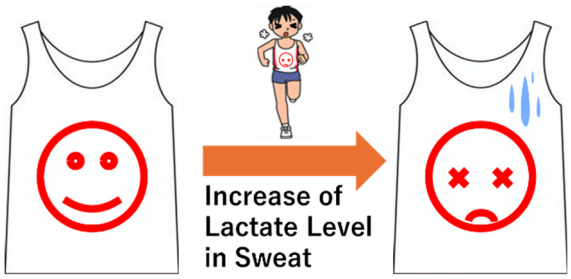

Fig. 1 Concept of our wearable lactate sensor with dynamic visual pattern responses

Experimental

An outline of the sample preparation is shown in Fig. 2. The cotton fabric was cut into 6 cm × 6 cm pieces, washed with water and acetone, and dried with cold air from a hair dryer. In a glove box replaced with nitrogen to reduce the oxygen concentration to about 1.0%, 0.15 mL of the monomer solution for non-responsive area (Table 1) was dropped onto the cotton fabric with photomask 1 attached. After irradiation with UV light (365 nm) through a photomask for 19 h, the cotton fabric was immersed in 100 mL of distilled water and stirred in an incubator at 25 °C for 1 h. The washed cotton fabric was then immersed in an anionic dye solution ([dye] = 1 mM, pH 7.4 by 10 mM HEPES) and stirred in an incubator at 25 °C for

10 min. The colored cotton fabric was then immersed in distilled water, washed, and dried in cold air using a hair dryer. After trimming the edges of the cotton fabric by 5 mm, the process was repeated with the monomer solution for the lactate-responsive area (Table 1) and photomask 2.

Table 1. Monomer compositions[a)]

Pattern area	[Monomer] / mM			
	1	2	3	4
Lactate-responsive	800	200	0	400
Non-responsive	0	50	950	400

[a)]Initiator: AAPH (90 mM), Solvent: MeOH:H_2O = 3:2 (v/v).

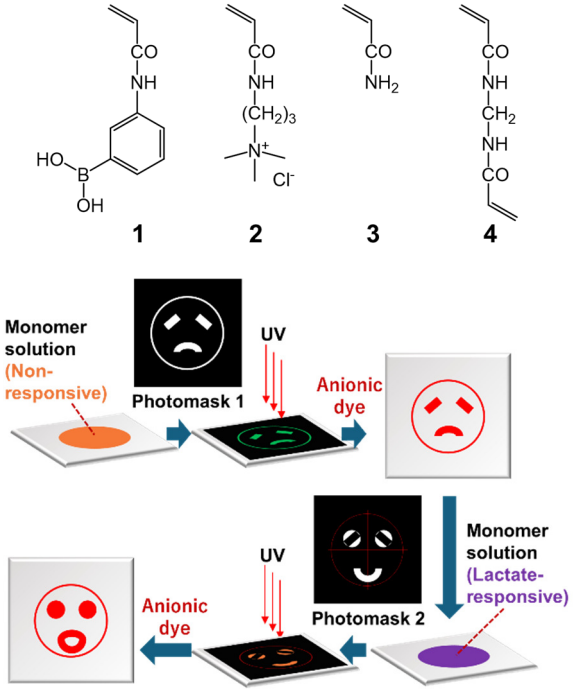

Fig. 2. Fabrication process of the facial pattern sample.

Results and Discussion

Facial pattern samples were prepared by using two different monomer solutions and their corresponding photomasks. Two anionic dyes, Indigo (Indigotrisulfonate) and AR18 (Acid Red 18), were used for coloring. When these samples were immersed in a 100 mM lactate solution, the smiling pattern changed over time and transformed into a crying face (Fig. 3). No major differences in response behavior were observed between the dyes. To numerically evaluate these pattern changes, the RGB values of the lactate-responsive and non-responsive areas in the sample photographs were determined. In the case of the Indigo-colored samples, the R and G values increased significantly in the lactate-responsive area, whereas the increase in the B value was relatively small. In contrast, in the non-responsive area, the R and B values showed only slight changes, and the increase in the G value was small compared to that in the lactate-responsive area. For the AR18-colored samples, the G and B values increased significantly in the lactate-responsive area, whereas the R value decreased slightly. In contrast, in the non-responsive area, the increases in the R and B values were small compared to those in the lactate-responsive area, and the G value showed virtually no change.

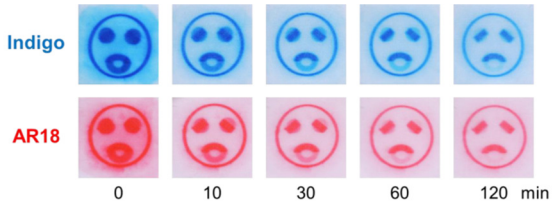

Fig. 3. Lactate-responsive changes in the facial pattern samples immersed in 100 mM lactate solutions.

Next, we examined changes in the pattern as a function of lactate concentration in samples colored with AR18. As shown in Fig. 4, changes in the pattern in response to lactate appeared as the response time increased. When the response time was 120 min, the pattern completely changed from a smiling face to a crying face as the lactate concentration increased from 0 to 100 mM. These results indicated that the dye preferentially desorbed from the lactate-responsive areas in the pattern and changed to a different pattern based on the dye remaining in the non-responsive areas.

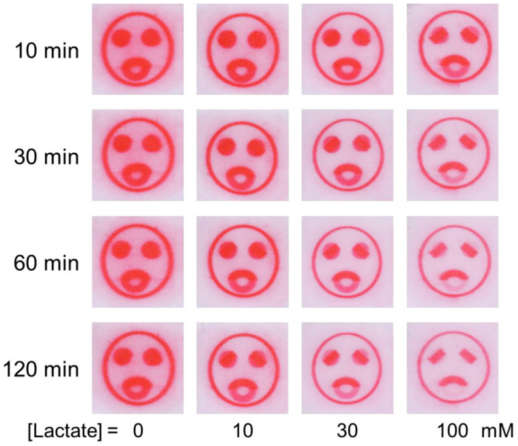

Fig. 4. Pattern changes of the facial pattern samples stained with AR18 after immersion in aqueous lactate solutions.

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