

SENSING SWEAT IN REAL-TIME USING WEARABLE MICRO-FLUIDICS

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ABSTRACT

A wearable, robust, flexible and disposable micro-fluidic chemical barcode platform that incorporates novel ionic liquid polymer gels (ionogels) is presented. The device has been applied to the monitoring of sweat pH in real-time during an exercise period. The micro-fluidic structure ensures that fresh sweat is continuously passing through the sensing area providing the capability to perform continuous real time analysis ensuring immediate feedback regarding sweat composition.

KEYWORDS: : pH, sports science, sweat monitoring, wearable sensors, chemical barcode, micro-fluidics

INTRODUCTION

Nowadays, wearable sensors such as heart rate monitors and pedometers are in common use. Several products are already on the market, such as the Lifeshirt®, developed by Vivometrics®, the body monitoring system developed by BodyMedia®, miCoach gear by Adidas and the Nike-Apple iPod Sports kit which facilitates individualised feedback of performance during exercise periods. The use of wearable systems such as these for personalised exercise regimes associated with health and rehabilitation is particularly interesting. This area is growing exponentially, as the economics of healthcare increasingly point to the need to provide remote monitoring of patient progress, rather than the current hospital focused model. In particular, the true potential of wearable chemical sensors for the real-time ambulatory monitoring of bodily fluids such as tears, sweat, urine and blood has not been realised due to difficulties associated with sample generation, collection and delivery, sensor calibration and reliability, wearability and safety issues.[1]

Micro-Total-Analysis (μ TAS) or Lab-on-a-Chip (LOC) is an important concept for the development of personalised health care and point of care diagnostic devices. Important technological barriers such as miniaturisation, low cost production, reusability or disposability, robustness, flexibility and adaptability are continuously being overcome using this approach. However, sweat, which is easily accessible using non-invasive means, remains largely unexplored as a sample medium for tracking personal health status using the LOC approach.[2]

EXPERIMENTAL

The micro-fluidic platform (20 x 17 mm) consisting of four independent reservoirs, was easily fabricated in poly(methyl methacrylate) and pressure-sensitive adhesive in five layers using the CO₂ ablation laser, Figure 1. The fabrication protocol consists of a 125 μ m thick PMMA base layer followed by a layer of PSA (80 μ m) with the channels, and another PMMA (125 μ m) which contain four rectangular reservoirs (2 mm x 6 mm) in which the ionogel was polymerised. To seal the system, a lid consisting of two layers, PSA (80 μ m) and PMMA (125 μ m), was glued to the previous three layers by lamination. The lid contains four holes (1 mm x 5 mm) also fabricated using the CO₂ laser. The holes were carefully arranged to site directly over the polymerised ionogels.

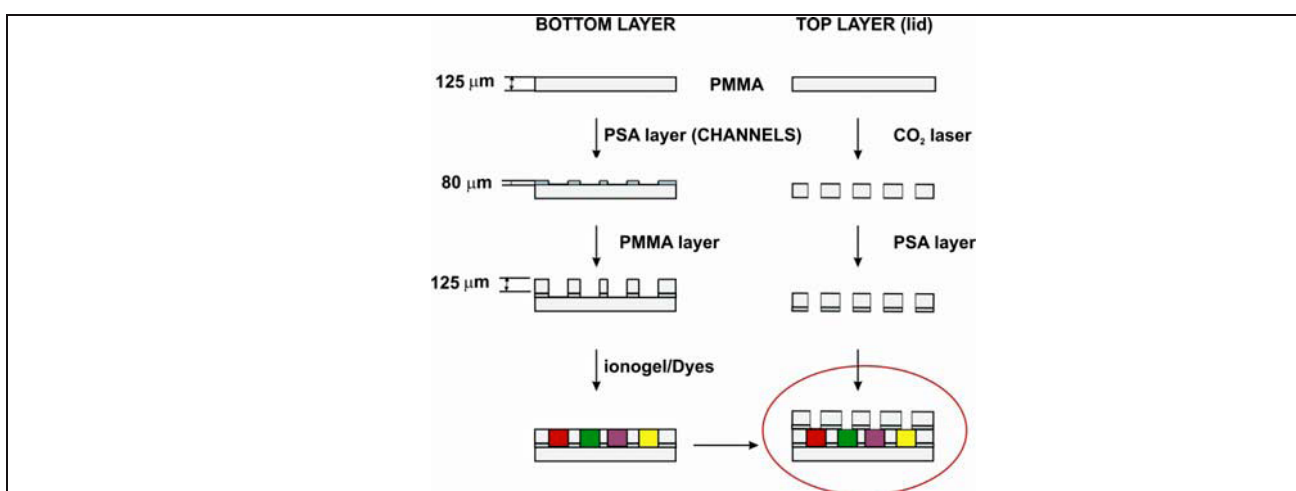


Figure 1: Micro-fluidic chip fabrication process.

RESULTS AND DISCUSSION

It is demonstrated in this work that pH values can be obtained by simply observing the barcode colour variation in comparison to a standard colour chart or through more sophisticated methods such as video analysis of the colour changes. A significant advantage of these approaches is that the on-body sensor consumes no power, does not require

any electronics for signal acquisition or communication, and therefore does not need a battery [1]. The sensing function is provided by pH indicator dyes immobilized within an ionogel polymer matrix, Figure 2.

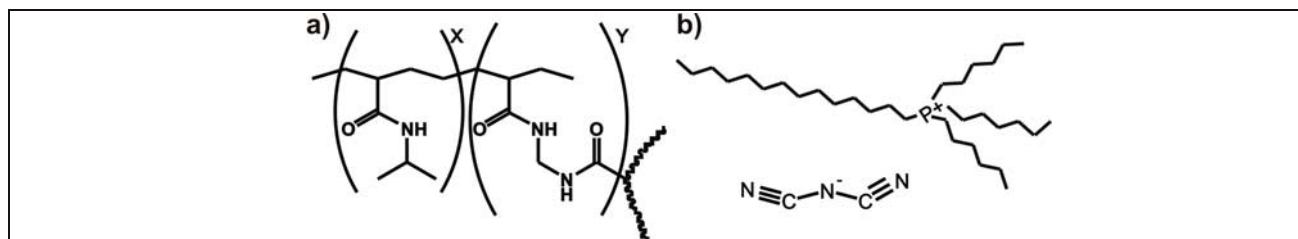


Figure 2: The molecular structure of the two components that make up the ionogel material. a) poly(*N*-isopropylacrylamide) and *N,N*-methylene-bis(acrylamide) cross-linked polymer in the ratio 100 (*x*):5 (*y*), and b) the ionic liquid trihexyltetradecyl-phosphonium dicyano-amide [$P_{6,6,6,14}$][*dca*].

Due to ion-pair interactions between the various pH indicators and the ionic liquid that forms the ionogel structure, there is no leaching of pH dyes during the experiments[3]. Since the micro-fluidic system is fabricated using very thin PMMA and PSA layers (Figure 1), the whole device is flexible and can easily adapt to the body contours. Moreover, it is comfortable to wear providing an unobtrusive and non-invasive method for the analysis of sweat during exercise. The chemical sensor barcode can be encapsulated into an adhesive plaster (Figure 3) or integrated in sports clothing. Particularly simple to implement is integration into a sweat band worn on the head or the wrist from which information about the sweat chemistry can be obtained directly during exercise.

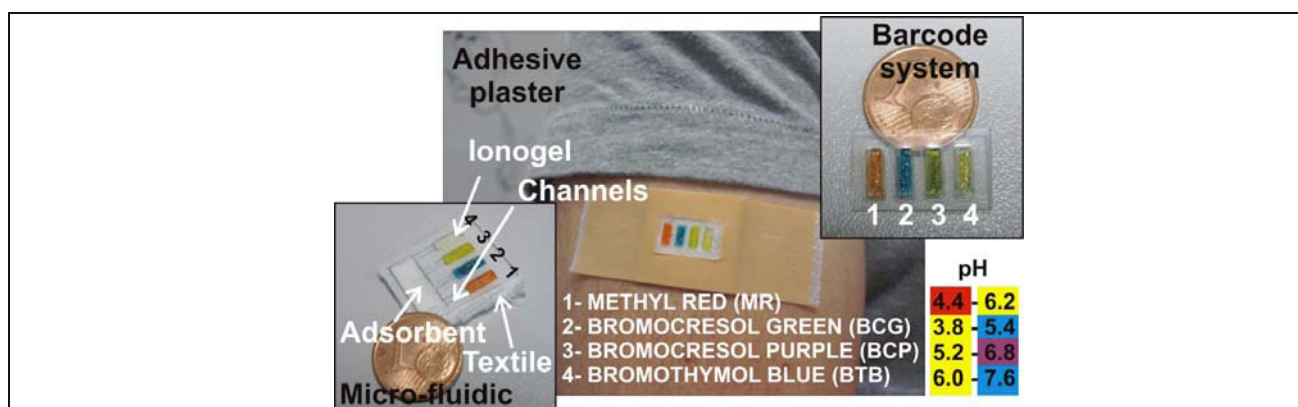


Figure 3: Digital images of the barcode (up right side), the micro-fluidic platform (down left side) and the incorporation of the platform into a commercially available adhesive plaster (centre); pH dye names and active pH range.

The design of the micro-fluidic structure ensures that fresh sweat is continuously sampled from the skin and flows past the ionogel-sensors throughout the entire training period. In Figure 4a,b, sweat is absorbed by the fabric of the clothes and comes in contact with the barcode sensor. The dyes react with the sweat and change colour according to their respective pKa's. Sweat is drawn continuously through the micro-fluidic device by the super-adsorbent material, which acts as a passive pump, in effect sucking the liquid through the micro-fluidic channel. The micro-fluidic system is easily calibrated in a conventional manner using standard buffer solutions. Each of the dyes exhibits a characteristic colour depending on the pH of the buffer which can be plotted against the pH value as shown in figure 4c for the indicator bromothymol blue (BTB).

Figure 5 presents the results of a real experiment obtained with the sensors during an exercise event. It was observed that the colour of each of the pH indicators in the ionogel matrix varies with the pH of the sweat over time except methyl red (MR) indicator probably due to interference by the ionic liquid anion [*dca*], which is known to behave like a Lewis base [4]. However, the bromocresol green ionogel sensor correlates reasonably well with the commercial pH probe reference measurements.

CONCLUSION

The approach presented here can provide immediate feedback regarding sweat composition, pH, to individuals during exercise period. A particular colour pattern of the barcode corresponds with a defined pH of the sweat with an accuracy of 0.5 pH units. This can be measured by eye or by video analysis. More sensitive quantitative measurements can be attained by integrating optical sensing components controlled by a wireless micro-controller.

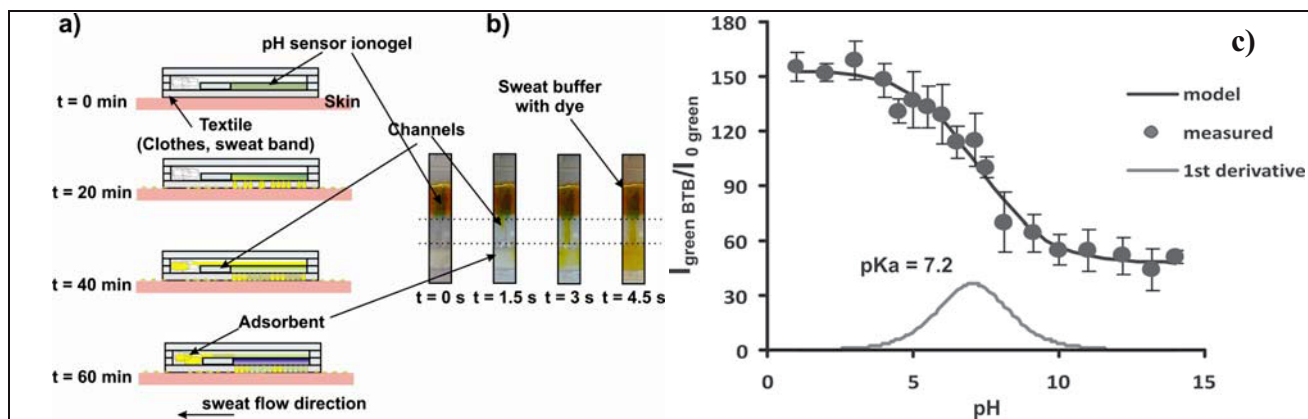


Figure 4: a) Schematic representation of the micro-fluidic system performance. b) Series of pictures showing the channel performance in the micro-fluidic system. c) Calibration curve showing pH vs. green intensity of bromothymol blue ($n = 3$) from the micro-fluidic system pictures taken at each pH.

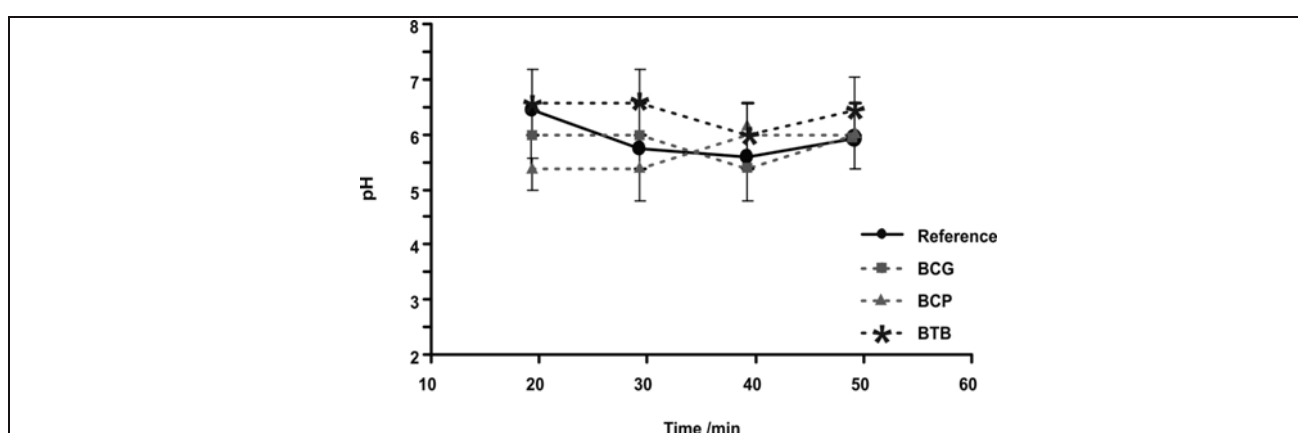


Figure 5: Digital Sweat pH determination using the micro-fluidic device in an individual during a 50 minutes training period.

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