proceedings

Eurosensors PARIS 2017 September 3-6 • 2017 • XXXI conference

MDPI

Proceedings

Stretchable Material for Microfluidic Applications †

Yves Fouillet [1,*], Charlotte Parent [1], Giacomo Gropplero [1], Laurent Davoust [2], Jean Luc Achard [3], Frédéric Revol-Cavalier [1] and Nicolas Verplanck [1]

[1] DTBS, Leti, CEA, University Grenoble Alpes, F-38000 Grenoble, France; charlotte.parent@cea.fr (C.P.); giacomo.gropplero@orange.fr (G.G.); frederic.revol-cavalier@cea.f (F.R.-C.); nicolas.verplanck@cea.fr (N.V.)
[2] SIMaP, CNRS, University Grenoble Alpes, F-38000 Grenoble, France; laurent.davoust@simap.grenoble-inp.fr
[3] LEGI, CNRS, University Grenoble Alpes, F-38000 Grenoble, France; jean-luc.achard@legi.grenoble-inp.fr
* Correspondence: yves.fouillet@cea.fr; Tel.: +33-4-3878-9274
† Presented at the Eurosensors 2017 Conference, Paris, France, 3–6 September 2017.

Published: 18 August 2017

Abstract: Materials selected for microfluidic technology exhibit mechanical properties that can be a source of innovation. For instance, devices that take advantage of rigid (glass, silicon) or soft (elastomer, PDMS) materials, as well as porous materials, such as paper, are widely reported in the literature. In this paper, we illustrate the potentialities of hyper elastic materials for lab-on-chip developments. Two breakthrough examples are reported: (i) a new digital microfluidics approach based on a stretchable membrane for addressing a large range of liquid volumes in complex protocols and (ii) a new low-cost approach for prototyping fully deformable microfluidic devices based on a polymeric foam.

Keywords: microfluidics; hyperelastic; stretchable; lab on a chip; polymeric foam

1. Introduction

Many examples of microfluidic systems reported in the literature are fabricated from PDMS. The large elasticity of this silicone makes the integration of microvalves and micropumps [1] easy. More recently, materials that exhibit deformability capabilities much larger than the one of PDMS have been introduced in different fields of applications such as soft robots [2] and stretchable electro-fluidic sensors [3]. The purpose of this work is to study how such materials can address some challenges in the field of lab on a chip applications. One difficulty is the integration of complex protocols using a microfluidic technology that can precisely handle discrete volumes ranging from µL to ml in a single platform. To this purpose, the first example presented here uses a hyper elastic membrane made of polymer (Ecoflex 00-50; Smooth-On Inc., Macungie, PA, USA) in order to integrate an array of collapsible chambers. Doing this, handling a high range of volumes—from one µL to hundreds of µL—is made possible. For other biomedical applications, the need for developing low-cost microfluidic devices in the context of point-of-care applications keeps growing. The second example presented in this paper is a low-cost system made from a polymeric foam (Bulpren PPI 90): prototyping in a fully deformable microfluidic device becomes possible.

2. Material and Methods

As an example of application that illustrates the interest of hyper-elastic membranes, a microfluidic device which creates six linear dilutions for a quantitative enzymatic assay was developed (Glucose assay kit GAGO-20, Sigma Aldrich, Saint Louis, MO, USA). The determination of glucose concentration requires a standard curve ranging from 1 to 5 fold dilution. To perform these dilutions, the chambers' volume ranges from a few µL to 100 µL. A key challenge is to handle precisely this high range of volumes in a simple way. This objective has been reached by defining

collapsible chambers using a stretchable membrane. The elastic membrane is made by spin-coating a 40 µm Ecoflex 00 50 layer (Smooth on, Macungie, PA, USA) at 3000 rpm for 6.5 s. This two-component silicone material exhibits a Young's modulus around 200 kPa and a maximal stretching ratio before tearing of about 980%, which is more than ten times higher than PDMS (see table below). The thin membrane is inserted between a fluidic card and a pneumatic card (a credit card format). Microfluidic patterns (channels, vias and semi-spherical caps) are directly machined from a Cyclic Olefin Copolymer (COC) sheet (TOPAS, USA) using a DATRON M7HP equipment. The membrane is simply bonded to the COC cards by using an adhesive devoted to silicone (Nitto Denko 5302A). The Ecoflex membrane is actuated pneumatically to properly fill and empty the hemispheric chambers. Figure 1a illustrates extreme positions of the successive strokes between two connected collapsible chambers. Valves are inserted between two consecutive chambers to avoid leakage. An area of such collapsible chambers allow the manipulation of multiple reactions. Thanks to the high elasticity of the membrane, the pressure of actuation can be very low (typically between 150 mbar and 500 mbar).

The second example is a low-cost microfluidic device based on a composite material. By using jointly an open-cell polyurethane foam (Bulpren PPI 90, Recticel, Belgium) and a hyper elastic polymer (Dragon Skin FX Pro), we are able to produce elastic fluidic channels (Figure 2).

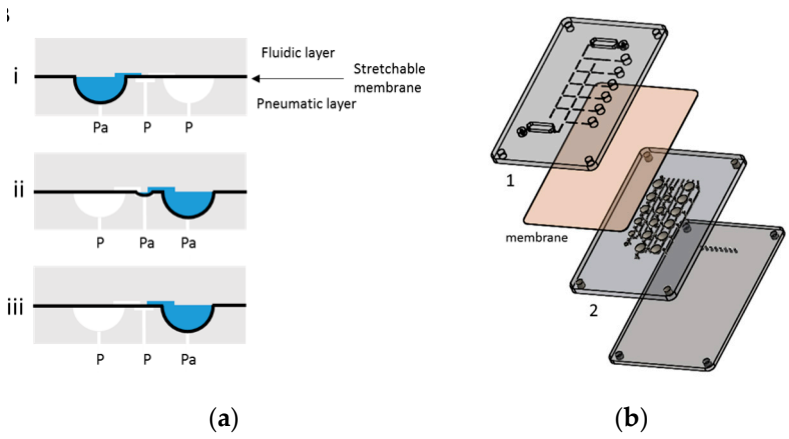

Figure 1. Hybrid cartridge made from 2 plastic cards and a stretchable membrane. (**a**) Schematic cross sectional view of fluidic actuation; (**b**) Perspective view of cartridge technology.

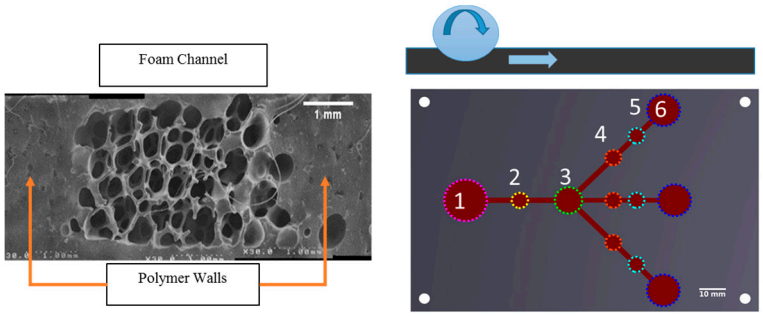

Figure 2. SEM image of a foam channel section. The liquid can flow through the porous matrix soaked in polymer (a). Top view of a fluidic pathway designed for a blood typing test. A rolling actuation induces the transport of biological samples through successive reservoirs (1: buffer; 2: blood; 3: mixing; 4: specific typing antibodies; 5: hollow chambers for visualization; 6: wastes).

The fabrication process here benefits from the high viscosity of the Dragon Skin initially used at liquid state. The latter penetrates entirely the foam while its high viscosity prevents it from spontaneously flowing out. Once the foam is fully saturated by the liquid polymer, the channels are designed by embossing. The Dragon Skin polymer is therefore expelled from the foam at the specified

locations which correspond ultimately to channels or reservoirs. When the polymer is fully cross-linked, the whole device and therefore the channels so built are stretchable because the mechanical properties of both foam and silicone are purposely similar (Table 1). More details on the technology and the modeling of this foam-based approach can be found in [4]. Because the polymerization time of Dragon Skin is only few minutes, the cycle of fabrication can be very short. Based on a controlled and repeatable embossing technique, the manufacturing process is compatible with mass production. A channel network dedicated to a blood typing test is presented in Figure 2.

Table 1. Mechanical properties of different hyper-elastic materials used for microfluidics applications compared to conventional PDMS.

Material	Maximum Elongation	Young Modulus
PDMS	7 to 40%	0.8–3 MPa
Ecoflex 00-30	900%	170 Pa
Dragon skin	760%	560 kPa
Bulpren PPI90	350%	~22 kPa (elastic phase)

3. Results and Discussion

3.1. Enzymatic Assay Validation Using Stretchable Digital Microfluidics

We propose here a new technology based on a hyper elastic membrane to fabricate collapsible chambers with large volume and particularly with high aspect ratio (such as hemispheric chambers of a few millimeters). One interest of using a hyper elastic membrane between two solid polymer layers is to precisely calibrate volumes at low pressures for a wide range of volumes without deforming the bulk material. To validate the integration of a dilution range in a biological assay, an architecture to quantify glucose concentration in a sample has been developed. First, protocol steps have been validated by using dyed water (Figure 3). Visualization shows that the fluidic actuation by a stretchable membrane offers the possibility to handle volumes from microliter to hundreds of microliter and allows good fluid filling and draining. The first step which is the reagent volumes calibration is performed without air bubbles in a reproducible manner. Then the glucose solutions and the diluent solutions are mixed to obtain different concentrations of glucose. After that, the solutions are mixed to the reagent 1 (enzymes) and 5 min later to the reagent 2 (sulfuric acid) to stop the reaction. In this architecture, the first line is the sample which is represented by a solution of glucose diluted per 2. Finally, 20 µL of each solution are pipetted in the exit wells and transferred in microwells for absorbance measurements at 540 nm using a spectrophotometer (TECAN infinite M1000, CH). Mean values with standard deviation bars of 5 repeats have been plotted (Figure 3e). The calibration curves show a good linearity and the absorbance of the sample which is represented by a solution diluted per 2 corresponds to the expected value.

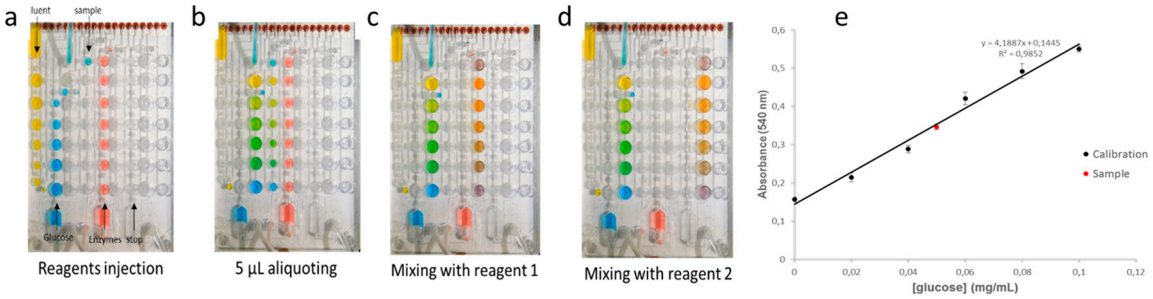

Figure 3. Validation of glucose assay with on chip calibration curve: Protocol steps (**a**–**d**). Plots of absorbance intensities at 540 nm depending on the dilution factors (**e**).

3.2. Foam-Based Device for Point of Care Applications

The production process for a new microfluidic foam-based device relies on the combined use of a polymeric foam and an elastomer with highly elastic features essentially issued from the structural properties of the foam. Thus, foam microfluidic devices offer, besides capillarity, a decisive advantage: the possible use of either a manual compression or an external peristaltic actuation for monitoring of microfluidic flows [4]. Basic operations were studied in order to validate the feasibility of performing a diagnostic test (liquid sample preparation, deposition or removal, biological detection). Filtration of objects a few tens of micrometers sized is made possible by applying a controlled compression on the foam channel. The fluorescent or colorimetric detection of biological elements is equally possible by means of isothermal DNA amplification. The blood typing design on Figure 2 was fabricated and validated. The blood typing protocol can be performed by simple finger actuation or with a roller that induces a peristaltic effect. This test is carried out on an integrated foam-based device which highlights the following benefits: robustness, user-friendly, embedded reagents (liquid or dried), multiple materials combination and motion of a biological sample from a simple external compression. The blood aggregation is clearly made visible in the visualization chamber presented in Figure 4e.

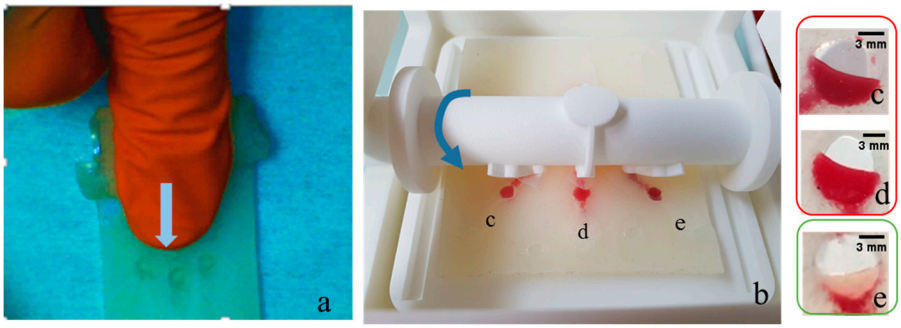

Figure 4. Blood typing test in fully flexible foam-based microdevice which can be manually wrapped for the generation of a Poiseuille flow (**a**); similar effect is obtained with a roller (**b**); Specific typing antibodies embedded in the device allow visualization of the blood type—negative (**c**,**d**); positive (**e**)—in dedicated hollow chambers.

4. Conclusions

The potentialities of hyper elastic materials for lab-on-chips was illustrated with two examples. First, a new digital microfluidic technology allowing to address a large range of discrete volumes in complex protocols was validated for an enzymatic assay. This protocol requires fluidic functions such as volume calibrations, linear dilutions, fluid transfer, mixing, aliquoting which are common operations in many biological assays. Second, a low-cost approach for prototyping fully deformable microfluidic devices from a polymeric foam was validated. The foam-based fluidic approach is thought of as a relevant complement to existing microfluidic techniques essentially based on networks of channels or on the use of capillarity such as in paper-based microfluidics.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Unger, M.A.; Chou, H.P.; Thorsen, T.; Scherer, A.; Quake, S.R. Monolithic microfabricated valves and pumps by multilayer soft lithography. *Science* **2000**, *288*, 113–116, doi:10.1126/science.288.5463.113.
2. Wehner, M.; Truby, R.L.; Fitzgerald, D.J.; Mosadegh, B.; Whitesides, G.M.; Lewis, J.A.; Wood, R.J. An integrated design and fabrication strategy for entirely soft, autonomous robots. *Nature* **2016**, *536*, 451–455, doi:10.1038/nature19100.

3. Pineda, F.; Bottausci, F.; Icard, B.; Malaquin, L.; Fouillet, Y. Using electrofluidic devices as hyper-elastic strain sensors: Experimental and theoretical analysis. *Microelectron. Eng*. **2015**, *144*, 27–31, doi:10.1016/j.mee.2015.02.013.
4. Gropplero, G.; Davoust, L.; Arnoux, S.; Fouillet, Y.; Revol-Cavalier, F. Foam-based microfluidics: experiments and modeling with lumped elements. *Microfluid. Nanofluid*. **2016**, *20*, doi:10.1007/s10404-016-1832-0.