Evaluation of Piezoresistive Polymer-based Traces for Non-invasive Sensor Patch

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Abstract

In this paper, we shall discuss the suitable alternative material to gold for creating traces or electrodes of a non-invasive flexible sensor patch that is used for detecting early extravasation during intravenous cannulation. The samples were prepared by printing 5 µm- to 10 µm-thin piezoresistive polymer-based Carbon paste on a base polymer patch, also called the adhesive film. The first samples have the traces embedded in between two base adhesive films. The sensitivity of the samples was characterized by using a pressure chamber/ jig with 4 cm hole to mimic an extravasation by bump formation when pumped with compressed dry air (CDA) that is connected to a 15 psi source. The sensitivity value obtained was 20% up to 23% at 0.16 psi. After optimization of the curing temperature of the adhesive film and piezoresistive polymer-based Carbon traces, ex-vivo test was conducted with the prototype sample placed on the cannulation site of a pork front hock. At 2 ml and 5 ml infused fluid, the sensitivity obtained is only 1.1% and 2.44%, respectively. The overall prototype dimension of all samples is 6 x 7 cm^2. The second samples were prepared with narrower trace width and spacing than the first samples. Sensitivity obtained from the second sample at 0.16 psi increased to 50% up to 79%. The third samples were prepared with the same narrow trace with as the second sample, but this time the piezoresistive polymer-based traces were not embedded in two adhesive films, making the sample a single layer patch only. Sensitivity obtained at 0.16 psi increased further to 140% up to 200%. The 0.16 psi read-out is based on previous data that at this pressure induced in the 4 mm hole where the adhesive film is placed over, it translates to 3mm bump height at 2ml infused volume on the skin. The results suggest a strong potential in the development of the piezoresistive polymer-based Carbon traces for flexible non-invasive sensor patch for early extravasation detection.

Introduction

Non-invasive detection and measurement of physiological characteristics has come a long way and has been practiced widely for quite some time. Common physiological properties such as body temperature, heart rate, and oxygen saturation are non-invasively monitored and measured [1] [2]. Non-invasive sensors, be it in rigid or flexible packaging or carriers, are developed for this purpose. Sensing types and functions also varies widely. Some provide only a single sensing function (i.e. body temperature only or skin stretch only) while others have multiple or multi-modal sensing functions (i.e. combination of heart rate and body temperature) [3]. Regardless of the form or function, users, patients and healthcare practitioners alike favor these non-invasive sensors because of their practicality, ease of use, and no unnecessary worries of further infections while in use.

Clinical Need

Intravenous (IV) is placed into a vein in order to have venous access for blood sampling and blood products or to give fluid or medicine that works best only through this method of delivery or when a person or patient could not take anything orally [4]. The cannulation site is the point at which the cannula enters the skin. Extravasation injury happens when the IV fluid or medicine accidentally leak from the intended vein [5], causing it to form a bump on the cannulation site or a severe tissue injury or worse, cause the cells and nerves in that area to die which may further lead limb amputation. Extravasation detection equipment are available but they are bulky, cumbersome, and expensive [6].

Institute of Microelectronics, Singapore, has developed a disposable and flexible non-invasive sensor patch for early extravasation detection. The physiological property that the sensor patch monitor and measure is the skin tension or skin stretching when a bump is formed on or around the cannulation site. Its strain sensing method creates a piezoresistive effect that it measures the change in resistance value of the gold (Au) electrodes or traces that is embedded in the developed sensor patch [7]. Gold is the final material used for the traces of the patch after several materials were considered and evaluated (i.e. Aluminum, Copper, and with or without a combination with Titanium were also evaluated). Its ductility allowed it to be processed such that it conforms to the base adhesive film or patch and to the contours of the skin when pasted on top of it. It is also suitable because it does not oxidize easily. The resulting flexible sensor patch, as characterized and confirmed through benchtop tests, ex-vivo tests using pork front hock, and in-vivo trials, is sensitive enough to detect even the slightest stretching or swelling of the skin.

At this point, it is proven that the patch with gold traces is working. However, with the soaring price of gold and the way it is processed to integrate with the flexible adhesive film to form a patch, an alternative material to gold needs to be evaluated for performance comparison, possible mass manufacturability, and cost consideration.

Materials and Method

Trace Material Comparison

Previous work done on the sensor patch used gold as traces or electrodes for strain sensing that created piezoresistive effect. The actual developed flexible and disposable non-invasive sensor patch is shown in Fig. 1(a). It looks basically like the normal adhesive film dressing used in hospitals but with added insulated wire and end header pins to allow for resistance testing. The gold traces, created by metal deposition is embedded in two adhesive films, as shown in Fig. 1(b).

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In this work, the piezoresistive material used is a polymer-based Carbon that is screen-printed on a flexible adhesive film. The samples are prepared using similar design as the previous sensor patch with gold traces. The critical issue that needs to be addressed to successfully change the gold material into a piezoresistive polymer-based material is not only the cost-consideration (i.e. material type and manufacturability) but mainly the sensitivity of the traces or electrodes in strain sensing function. To address this issue, two different methods in preparing of the samples are done. As shown in Fig. (2), the first and second samples are prepared with the traces embedded in two adhesive films and the third samples are prepared using only a single layer of the adhesive film. Both sample types are then characterized and tested using the established testing as for the sensor patch with gold traces.

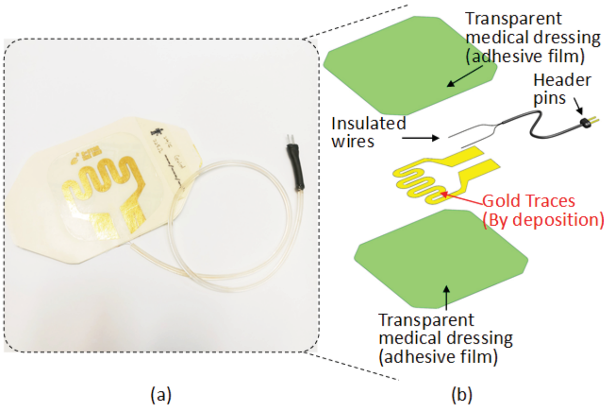

Fig. 1. (a) Developed sensor patch shows the gold traces by metal deposition and (b) the exploded view of the sensor patch showing that the Gold traces are embedded in the adhesive film.

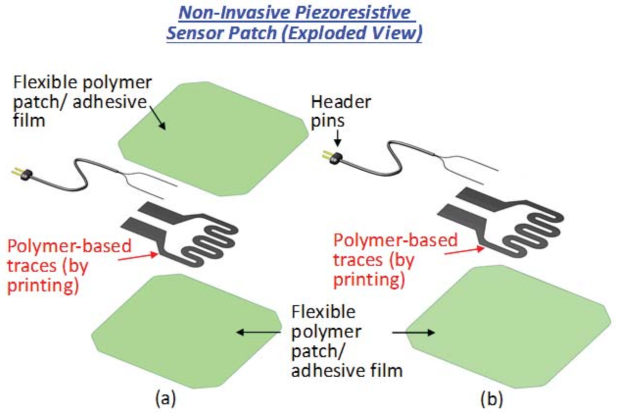

Fig. 2. Representation of two sample types (a) First samples have Carbon traces embedded in two adhesive films. Second samples are the same except for narrower trace spacing, while the (b) third samples are prepared only using a single layer of adhesive film.

Adhesive Film Characterization

The adhesive film by itself is a medical grade transparent dressing. It is composed of a (top) paper-frame dressing and a printed paper liner, which once removed, exposes the adhesive surface of the dressing. It is imperative to remove these paper frame and liner during application to the skin. Before any type of polymer-based carbon could be printed as the traces on the adhesive film, the maximum curing temperature and time that the adhesive film could withstand while still able to release the paper frame and liner need to be characterized. Using the previous work as baseline parameters, i.e. the combination curing time and temperature of non-conductive epoxy on the adhesive film, the evaluation is conducted using 80 °C ~ 120 °C and 10-20 minutes. Table 1. shows that the maximum curing temperature and time that could be used for further processes and evaluations is only 80 °C and 10-20 minutes.

Table 1. Adhesive Film Characterization.

Run No.	Curing Temperature [°C]	Curing Time [min]	Result	
			Paper Liner Released	Paper Frame Released
1	120	10	Yes	No
2	120	15	Yes	No
3	120	20	Yes	No
4	100	10	Yes	No
5	100	15	Yes	No
6	100	20	Yes	No
7	80	10	Yes	Yes
8	80	15	Yes	Yes
9	80	20	Yes	Yes

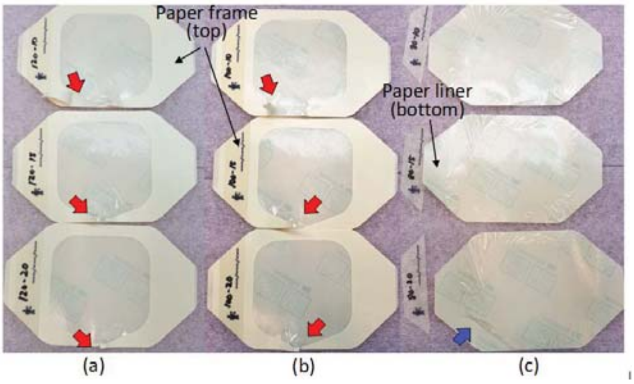

Fig. 3. Representative photos of the samples showing undetached paper frame from the adhesive film (red arrows) from (a) 120 °C (b) 100 °C samples and the adhesive film that could be detached from the paper liner (blue arrow) from (c) 80 °C samples. All cured from 10 – 20 minutes.

Piezoresistive Polymer-based Carbon Traces

After the curing temperature and curing time of the adhesive film is established, material for piezoresistive polymer-based traces/ electrodes is selected [8]. For mass manufacturability, screen printing process is utilized. Material selected is polymer-based Carbon paste that is specified for screen printing of working electrodes. The material is printed on the adhesive film at 5µm- to 10µm-thin and could be cured at either 60 °C for 30 minutes or at 80°C for 10-15 minutes.

Fig. 4 shows the different samples fabricated. Fig. 4(a) shows the first samples that are prepared exactly the same as the existing gold trace sensor patch. The second samples are prepared such that the design has narrower trace width and spacing, but also embedded, as shown in Fig. 4(b). The third samples also have the narrow trace width and space design but are prepared only with a single layer of adhesive film. It should be noted that none of the traces, not even the existing gold traces, of any design could directly contact the skin, as the traces are all created and use the adhesive film as its substrate or carrier.

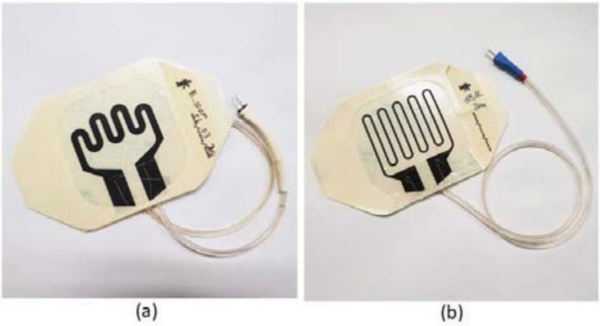

Fig. 4. Representative photos of the samples showing the polymer-based carbon traces that are able to perform strain sensing by piezoresistive effect. (a) Sample is exactly the same as the existing gold trace samples while (b) was prepared as both embedded and single layer.

Results and Discussion

Benchtop Testing

The samples are characterized using pressure chamber/ jig that is connected to a compressed dry air (CDA) source regulated at a maximum of 15 psi. The jig has four 1-4 cm holes, which are used to form bumps, mimicking the actual bump formation on the skin created from an extravasation injury. Fig. 5 shows the benchtop characterization and testing set-up. The jig hole used is 4 cm to standardize the data with most of the data from sensor patch with gold traces.

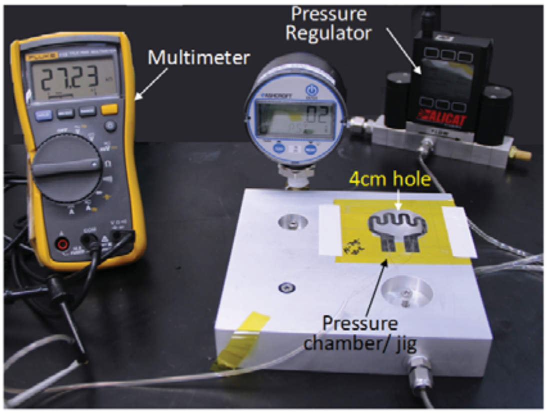

Fig. 5. Standard benchtop test set-up to characterize the piezoresistive sensor patch. Shown here is the first sample with polymer-based carbon trace having same design as the established sensor patch with gold traces.

The sensor patch is a passive device and the benchtop testing performed is a straight forward resistance measurement of the traces with respect to the change in the pressure induced in the jig from increased in CDA supply. Resistance readings are done at 0.02 psi iterations of CDA. It has been previously established from the data of the sensor patch with gold traces that 0.16 psi on a 4 cm hole in the pressure chamber/ jig results to approximately 3 mm bump height. This is about 2 ml infused fluid on the skin. The sensitivity of the piezoresistive sensor is defined and computed as the relative change in sensor trace resistance due to strain/ deformation of the sensor patch. Table 2 summarizes the sensitivity calculated from the results of the benchtop testing. Of the four sample types, the samples using narrow trace width and only has a single layer structure has the highest sensitivity at 140% - 200%. This reading alone shows that the polymer-based carbon has a high potential to replace the gold material.

Table 2. Benchtop Test Summary of Sensitivity.

S/N	Trace Material and Design	Final Sample type	Sensitivity
1	Gold – original design with 3 mm Trace Width	Embedded	40% - 50%
2	Carbon paste – original design with 3 mm Trace Width	Embedded	20% - 23%
3	Carbon paste – 1 mm Trace Width	Embedded	50% - 79%
4	Carbon paste – 1 mm Trace Width	Single Layer	140% - 200%

Ex-vivo Testing

To validate the results of the benchtop test, ex-vivo test is done using a piece of pork front hock. Porcine model (specifically subcutaneous layer of the pork skin, in this case) has been generally used since the previous studies due to its similarities with the human skin [9]. Fig. 6 shows the ex-vivo set-up prepared using a syringe pump to infuse colored water on a cannulation site to purposely form a bump on the pork skin. The polymer-based sensor patch is placed on top of the secured cannula and a multimeter is connected to its header pins. A 3D scanner is also fixed on top of the cannulation site in order to scan the site at each readout infused volume.

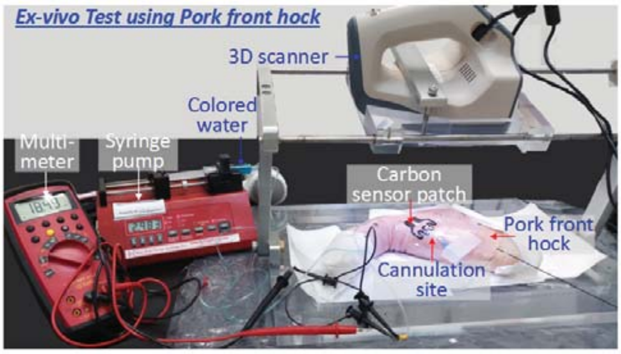

Fig. 6. Standard ex-vivo test set-up using porcine skin to form a bump on the cannulation site.

The ex-vivo test was conducted using the first two types of prepared samples, with critical readings expected at 2 ml and 5 ml infused volumes. The first samples have the exact same design as the gold patch, with the polymer-based traces embedded in the adhesive film. As shown in Fig. 7(a) and Fig. 8, at 2 ml infused volume on the pork skin, the bump height is measured at 1.2 mm with sensitivity of the patch only at 1.1%. At 5 ml infused volume, the bump height is at 1.94 mm with sensitivity of 2.44%. This result is much lower than the baseline sensitivity of 40% for gold. It could be due to fast diffusion of the infused fluid because of the variability in the cutting of the pork sample. It is also noted that the even at the benchtop test, the sensitivity of the first was also at 20-23% only. Fig. 7(b) shows the results of the second samples that have narrow trace width and space and are also embedded. At 2 ml infused volume, the bump height measured is 2.04 mm and sensitivity at 10.33%. At 5 ml infused volume, the bump height is measured at 3.1 mm with sensitivity of 15.26%. The third samples – design with narrow traces and single layer, have not been used for ex-vivo test yet as further bench top testing is being conducted because of its very promising results.

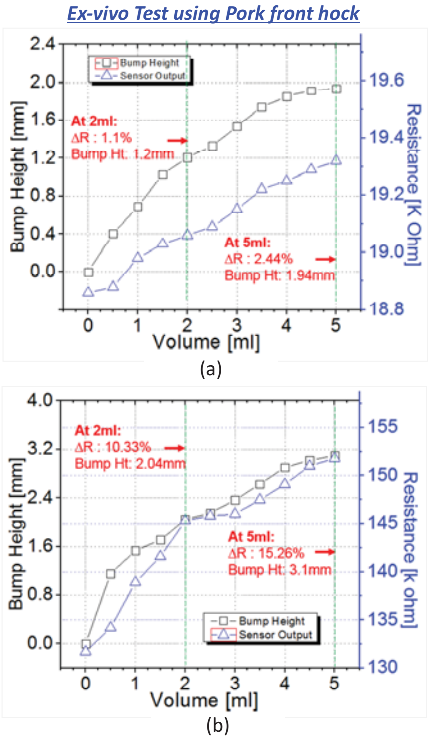

Fig. 7. Result of the ex-vivo test: bump height and resistance of polymer-based carbon traces against infused volume (a) using the existing 3mm design and (b) using narrow traces

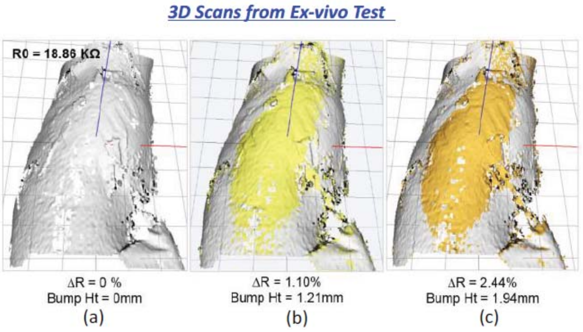

Fig. 8. Representation of the 3D scans from ex-vivo test conducted using the polymer-based sensor patch that have the exact same design as the gold patch.

Conclusions

With the results of the evaluation conducted, it is concluded that the chosen piezoresistive polymer-based material, i.e. Carbon paste, has a strong potential to replace the gold material as traces or electrodes of the flexible non-invasive sensor patch for early extravasation detection. Mass production by screen printing process is viable and definitely of lower material cost as compared to gold evaporation. By altering the design and dimension of the traces– specifically, the width, spacing, and thickness; and, by making the sample a single layer structure only, the sensitivity level also improved greatly. Further development of the sensor patch is possible to achieve and validate the desired sensitivity of the non-invasive sensor patches in in-vivo and clinical trial purposes.

Acknowledgments

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