A novel approach to transcutaneous localization of blood vessels using a dynamically reconfigurable electrode (DRE) array

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***Abstract*— non-invasive transcutaneous analysis is very desirable in medical applications that require blood analysis. Electrical impedance spectroscopy (EIS) is one of the many methods that has been extensively researched and is often used for such applications, with its advantages including very high sensitivity and rapid response. EIS utilizes electrodes to monitor conductivity variations in blood. However in order to minimize the effect of high impedance tissue and skin surrounding a low impedance, localized subcutaneous vascular structure of interest, one has to locate the structure of interest and then adjust the placement and size of the electrodes to make the measurement as targeted as possible. It is thus essential to achieve an appropriate method for a) detecting the vascular structure of interest and b) localizing the transcutaneous measurement so that sensitivity can be improved and greatly interfering measurements from surrounding tissue can be disregarded. This study proposes and assesses the potential use of a multi-electrode array for making dynamically reconfigurable electrodes (DRE), by treating electrode segments as pixels that can form re-locating and re-shaping electrodes. Simulations preformed in COMSOL indicated that the technique can successfully locate a transcutaneous structure and achieve double the sensitivity relative to conventional electrode topologies.**

I. Introduction

Transcutaneous analysis of blood has been attempted using different monitoring methods in order to identify change in the composition of blood [1], [2]. One such method is electrical impedance spectroscopy (EIS) [3] which offers very high sensitivity and rapid response. The technique involves impedance measurements taken from the surface of the skin and can be carried out using a tetrapolar (four electrode) arrangement to minimize the influence of electrode properties to the measurements [4], [5]. The impedance measured can then be used to analyze different characteristics such as blood flow [6], levels of blood analytes like e.g. glucose [7] or even to carry out impedance cardiography [8]. In some or all of the above applications impedance measurements are taken by using ether band electrodes, which wrap loosely around a section of the body, or spot electrodes, which are usually disk shaped electrodes applied using adhesive tape [6], [8]. The problem associated with the use of such conventional electrodes is that the measurements of low-impedance blood variations are typically overshadowed by the high impedance of skin and tissue surrounding the region of interest. [5], [6], [9]. For transcutaneous analysis of blood it would be highly desirable for its impedance contribution to the measurement to be enhanced [3]. To achieve this, the electrodes would ideally need to be positioned directly over the blood vessels (Fig. 1a), however this would still require ether: a) the exact location of the targeted blood vessels to be known or b) visual inspection to be employed especially as the location of blood vessels differ from person to person. Even after the desired electrode positioning is identified, optimal fitting may require several attempts.

A possible solution to this challenge could be addressed by the use of multi-electrode array (MEA, similar to that used in [9]), whereby electrodes, could be dynamically addressed rather than physically re-positioned. However, in order to eliminate the need for visual inspection and alignment, a solution would be desirable for detecting the targeted structure prior to the measurement taking place. Moreover, in order to minimize unwanted impedance measurements from surrounding tissue, electrodes would ideally need to be physically shaped to a size corresponding to the diameter of the targeted vessel. Thus oversized electrodes would need to be "trimmed" whilst very small electrodes would entail a very high contact impedance, potentially limiting the output dynamic range of the current injection electronics and increasing thermal noise at the input of the measurement electronics [5].

The authors are researching a dynamically reconfigurable electrode (DRE) system that will allow the four electrodes of a tetrapolar configuration to automatically re-shape and re-locate so as to both trace and focus on a subcutaneous blood vessel (Fig. 1b). It will utilize a MEA, but with each electrode acting as a "pixel" that can be re-grouped and re-combined to form larger electrodes of different shapes and sizes and that can also be freely positioned at any location within the array.

In EIS such grouping of electrodes has not been reported, however it has been reported in other applications of electrical bio-interfacing such as electrical neurostimulation. Popovic-Bijeli et al. [9] developed a 24 segment electrode array for electrical stimulation of nerves in the arm, with segments combining to increase the size and to change the position of the stimulating electrodes. Lawrence et al. increased the number of segments (256) to improve the stimulation's selectivity [10].

Whilst the above methods were investigated for neurostimulation, to the knowledge of the authors they have not been proposed for use in transcutaneous impedimetric analysis of blood. Moreover, these studies presented the benefits of re-shaping electrodes but did not demonstrate their use for "mapping" the exact location of a structure of interest.

In this paper we carried out FEM simulations to assess the front-end of our tetrapolar DRE system, comprising a

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pixelated multi-electrode array for scanning and locating the position of a blood vessel followed by appropriately shaping and positioning electrodes (made of grouped pixels) such that they are directly over the targeted structure to refine transcutaneous blood impedance measurements. The sensitivity of the tetrapolar DRE front end was compared with that of large electrodes that have fixed size and static placement.

II. Methods

In order to assess the use of the DRE front end for use in transcutaneous blood analysis and to verify its use to detect the structure, a model of fat and blood was setup using FEM analysis in COMSOL 5.1 software and by solving Maxwell equations to measure the transfer impedance of the model.

A. Large electrode setup

A 3D model (Fig. 2) was designed in COMSOL 5.1 software, with a rectangular block set as a layer of fat with 3.9 mm depth, 17.1 mm height and 45.3 mm width. A cylinder positioned diagonally at a depth of 0.905mm away from the top was positioned inside the rectangular block, representing a blood vessel. Four co-planar rectangular electrodes where designed on the block's surface opposite to the blood vessel. Current carrying electrodes (CC - outer pair) were defined to be 8 mm high and 2 mm wide while pick-up electrodes (PU - inner pair) were defined to be 8 mm high and 1.5 mm wide. The distance between the inner pair of electrodes was set to 10mm center to center (as shown in Fig. 2). The shape and size of electrodes was chosen from an existing sensor. Simulations were performed using COMSOL's AC/DC module using a quasi-static solution of Maxwell's equations to solve for the electrical potential. The electrode/electrolyte interface double layer was not included in the simulation. The relative permittivity and electrical conductivity for blood and fat were taken from [11].

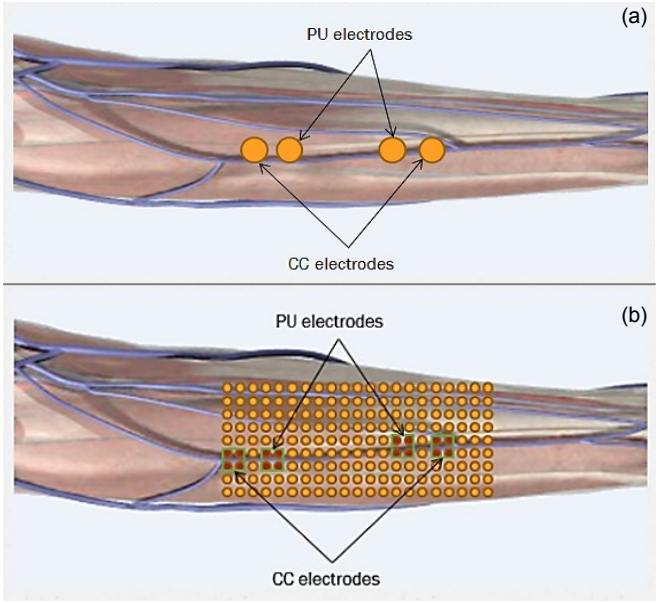

Figure 1: Tetrapolar configuration including current carrying (CC) and pick-up (PU) electrodes using a) fixed size and positioning (conventional setup), and b) DRE formed using a pixelated MEA.

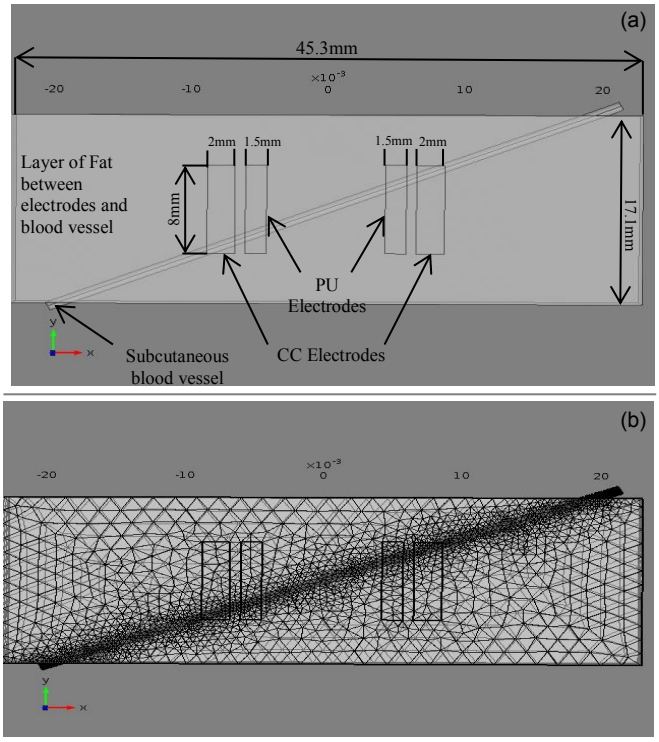

Figure 2: (a) COMSOL geometry top view of fat and blood with four rectangular electrodes, CC electrodes for current injection and PU electrodes for voltage measurement, and (b) a free tetrahedral mesh for the setup.

Two electric current models (ec and ec2) were set up one for the injection electrodes and one for the measurement electrodes. In both models the left electrode was set as the current injection terminal with a 1A current being assigned as a boundary condition and the remaining electrodes were set to ground terminal. A parametric sweep was set up which increased the conductivity of blood from its original value by 0.005S/m until the conductivity of blood was increased to 0.05S/m over the original conductivity. The sweep represents variations of blood analytes (e.g. ions) that would be measured by a transcutaneous EIS system and its purpose was to allow for the DRE sensitivity to be assessed in comparison to that of conventional electrodes.

B. DRE pixelated MEA setup

For the DRE setup, an identical second model was created, with the large electrodes replaced by an array of 8x16 round electrodes with a diameter of 0.6mm (Fig. 3). The array was designed such that two columns of 8 electrode pixels would equal the size of the first model's large measurement electrodes. The spacing between the elements of the array was setup to be 1mm center to center from the surrounding elements. This was done so that the array would cover the same area as the previously used large electrodes.

The next set of simulations was carried out in order to assess the ability of the DRE array to identify the location of the blood vessel. For this purpose, impedance measurements need to be taken from the entire area covered by the array. This simulation was carried out by keeping the conductivity of blood constant, the program then selected four electrodes horizontally adjacent to one another on the array (Fig. 4a) and ran the simulation, then changed the selection of

electrodes to the next four electrodes vertically below the previously selected ones (Fig. 4c) and ran the simulation again. This process was repeated till measurements were taken from all the eight rows of electrodes (array height), the program then shifted the selection of electrodes to the right horizontally by one electrode (Fig. 4b) and carried out impedance measurements for all eight rows. In this manner the program virtually scanned the entire area covered by the array.

C. Focused measurement simulation.

The results from the scan carried out in the second model (shown in the next section - Fig. 6), identified the location and optimum number of pixels positioned above the blood vessel, thus allowing the formation of the tetrapolar DRE configuration shown in Fig. 5. Each DRE consisted of four pixels. The resulting "focused" tetrapolar DRE configuration was then compared with the conventional tetrapolar configuration by using the same parametric simulation procedure that was used for the first model.

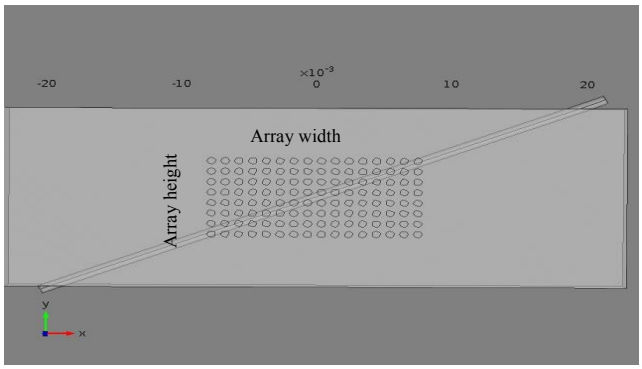

Figure 3: COMSOL geometry top view of fat and blood with an array of 8x16 electrodes that will be used for forming DREs

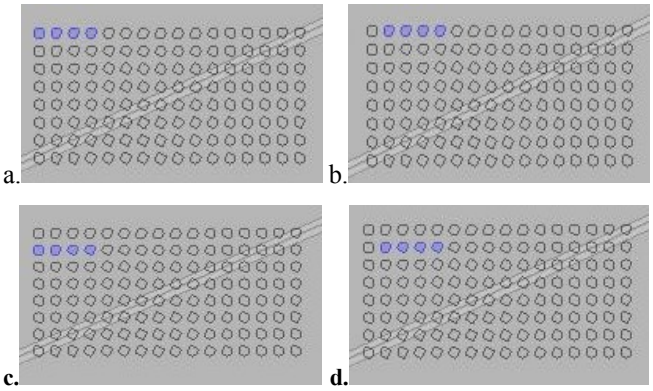

Figure 4. Electrode selections for impedance scan a) position of the four electrodes for first measurement, b) position of selected electrodes after shifting horizontally to the right, c) position of selected electrodes after shifting vertically down, d) position of selected electrodes vertically down after horizontally shifting right.

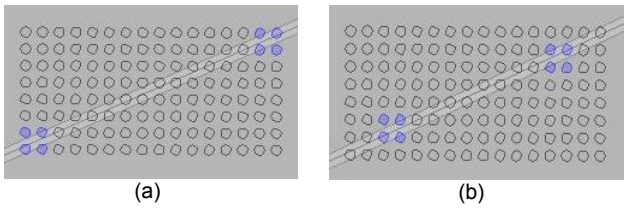

Figure 5. a) CC electrodes, b) PU electrodes, of the final DRE tetrapolar configuration, with their position and shape "focused" on the blood vessel, that has been determined by the on the scanning process (Fig. 6) .

III. RESULTS AND DISCUSSION

A. Multi electrode scan

The results from the scan were plotted to visualize the impedance of the area under the array (Fig. 6). From the plot it can be seen that the area where the blood vessel was located exhibited lower impedance from its surroundings, due to the high conductivity of blood which allows the majority of the injected current to flow through it, hence reducing the impedance measured locally by the sweeping four electrode pixels. In that manner the location of the blood vessel could be identified allowing for the selection of electrode pixels positioned above it to be grouped to form optimum DREs aiming towards a more focused impedance measurement.

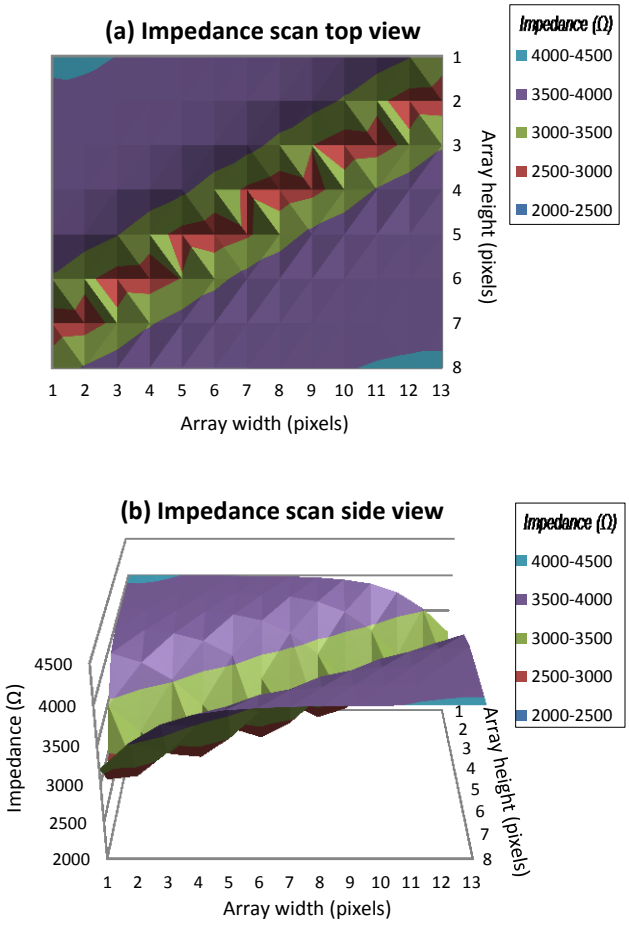

Figure 6. Impedance scan plot, a) top view, b) side view. The location of the low impedance subcutaneous blood vessel through the high impedance fat layer is clearly detectable, especially in (a).

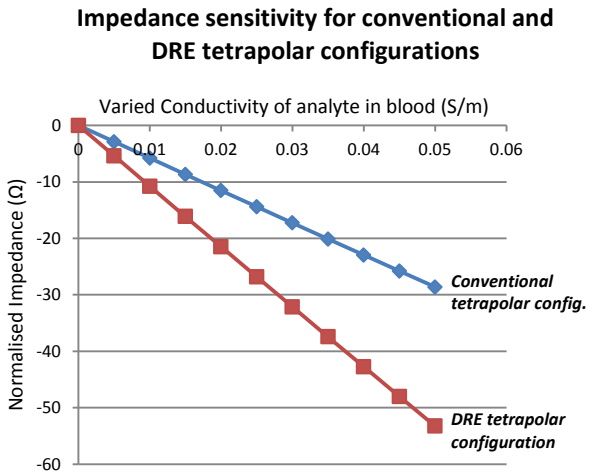

Figure 7: Comparison of both tetrapolar configurations in terms of their respective impedance sensitivity normalized to their respective baseline values. The impedance variation was a result of the same parametric conductivity sweep applied to both models.

B. Focused electrode results

The parametric impedance variation was applied to both the conventional "large" electrode tetrapolar configuration (1st model) and to the DRE tetrapolar configuration (2nd model) that was formed following the four electrode pixel scan-and-detect sweep described above. Measurements were plotted in Fig. 7 normalized to start from the respective baseline impedance measurement for each tetrapolar configuration. The results for the conventional model show that for each increment in conductivity of blood by 0.005S/m there was a decrease in measured impedance of approximately 2.86Ω ± 0.03Ω. For the same conductivity step the DRE configuration exhibited a decrease in measured impedance of approximately 5.32Ω ± 0.06Ω. This is almost double the change in impedance measured using the conventional electrodes. Thus, the comparison clearly indicates that the DRE configuration can greatly improve the sensitivity of EIS for transcutaneous blood analysis.

IV. Conclusion

In applications of transcutaneous blood analysis using impedance spectroscopy, the measurements from a subcutaneous blood vessel can be significantly degraded by the much higher impedance of surrounding tissue and skin. It is therefore desirable to accurately select the localization and size of the electrodes to be used. Within the context of their research towards a dynamically reconfigurable electrode (DRE) system the authors carried out COMSOL simulations to assess the performance of the system's front-end. This paper presented the results of these FEM simulations which were carried out to assess (a) the ability of a pixelated MEA to scan and detect a subcutaneous blood vessel and (b) the sensitivity of a DRE vs. a conventional electrode tetrapolar configuration in cases where a blood component changes its concentration.

The results indicated to a very satisfactory level that the proposed front-end is capable of scanning and detecting a subcutaneous blood vessel, below a layer of fat. This leads to the identification of the optimal size and positioning of electrode pixel groups that lead to the formation of DREs. The resulting "focused" tetrapolar configuration exhibits almost double the sensitivity of a conventional fixed shape and position electrode configuration. Therefore the proposed method can provide much more effective impedance measurements for non-invasive blood analysis.

References

[1] R. W. Stout, D. Y. Cho, S. D. Gaunt, H. W. Taylor, and D. G. Baker, "Transcutaneous blood gas monitoring in the rat.," *Comp. Med.*, vol. 51, no. 6, pp. 524–33, 2001.

[2] I. Bromley, "Transcutaneous monitoring–understanding the principles," *Infant*, vol. 4, no. 3, 2008.

[3] S. Kayashima, T. Arai, M. Kikuchi, N. Sato, N. Nagata, O. Takatani, N. Ito, J. Kimura, T. Kuriyama, and a Kaneyoshi, "New noninvasive transcutaneous approach to blood glucose monitoring: successful glucose monitoring on human 75 g OGTT with novel sampling chamber.," *IEEE Trans. Biomed. Eng.*, vol. 38, no. 8, pp. 752–7, 1991.

[4] R. H. Bayford, "Bioimpedance Tomography (Electrical Impedance Tomography)," *Annu. Rev. Biomed. Eng.*, vol. 8, no. 1, pp. 63–91, 2006.

[5] S. Grimnes and Ø. G. Martinsen, *Bioimpedance and Bioelectricity Basics*. 2015.

[6] C. Corciova, M. Turnea, and A. Salceanu, "A measurement system for the blood flow in peripheral territory," no. 4, pp. 1–4, 2011.

[7] A. Caduff, E. Hirt, Y. Feldman, Z. Ali, and L. Heinemann, "First human experiments with a novel non-invasive, non-optical continuous glucose monitoring system," *Biosens. Bioelectron.*, vol. 19, no. 3, pp. 209–217, Nov. 2003.

[8] J. J. McGrath, W. H. O'Brien, H. J. Hassinger, and P. Shah, "Comparability of spot versus band electrodes for impedance cardiography," *J. Psychophysiol.*, vol. 19, no. 3, pp. 195–203, 2005.

[9] A. Popovic-Bijelic, G. Bijelic, N. Jorgovanovic, D. Bojanic, M. B. Popovic, and D. B. Popovic, "Multi-field surface electrode for selective electrical stimulation," in *Artificial Organs*, 2005, vol. 29, no. 6, pp. 448–452.

[10] M. W. Lawrence, A. Brunschweiler, and T. Keller, "Multi-channel Transcutaneous Electrical Stimulation Environment," no. September, pp. 210–212, 2006.

[11] F.-J. Pettersen and J. O. Høgetveit, "From 3D tissue data to impedance using Simpleware ScanFE+IP and COMSOL Multiphysics – a tutorial," *J. Electr. Bioimpedance*, vol. 2, no. 1, pp. 13–32, 2011.