Comprehensive optimization of the tripolar concentric ring electrode with respect to the accuracy of Laplacian estimation based on the finite dimensions model of the electrode

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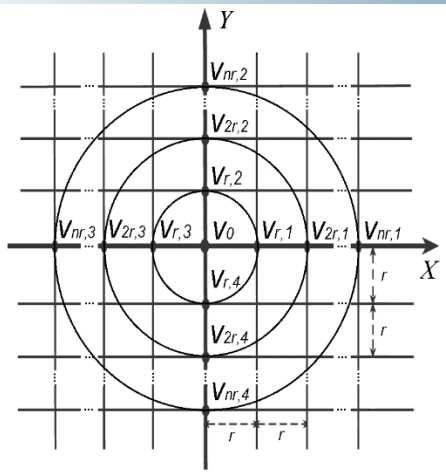
Introduction

- Until recently, all the research on concentric ring electrodes (CREs) was based on the negligible dimensions model (NDM; Fig. 1) of CRE which influenced electrode design (Fig. 2).

- Specifically, NDM has been used to propose the following ways to improve accuracy of surface Laplacian estimation:
  - Multipolar CREs [1];
  - Variable inter-ring distances CREs [2];
  - Optimized inter-ring distances CREs [3].

- Recently, finite dimensions model (FDM) was proposed offering significant advantages over NDM [4].

Figure 1. Negligible dimensions model (NDM) of the quadripolar (3 rings) concentric ring electrode (CRE) from [2].



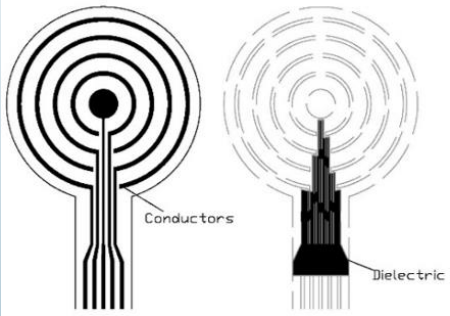


Figure 2. Pentapolar (4 rings) concentric ring electrode (CRE) from [4].

[1] Makeyev O., Ding Q., Besio W., (2016) *Measurement*, 80: 44-52
[2] Makeyev O., Besio W., (2016) *Sensors*, 16(6): 858
[3] Makeyev O., (2018) *BioMedical Engineering Online*, 17(117)
[4] Makeyev O. et al., (2019) *Applied Sciences*, 9(20):4279

Introduction

- Unlike NDN, FDM includes such electrode parameters as the radius of the central disc and individual widths of concentric rings (Fig. 3).
- This makes the FDM based optimization problem comprehensive since all of the CRE parameters are optimized simultaneously.
- The optimization criterion used in this study is maximizing the accuracy of the surface Laplacian estimation since ability to estimate Laplacian at each electrode constitutes primary biomedical significance of CREs.
- Results are illustrated for tripolar (2 concentric rings) CREs (TCREs) but can be extended to any higher number of rings.

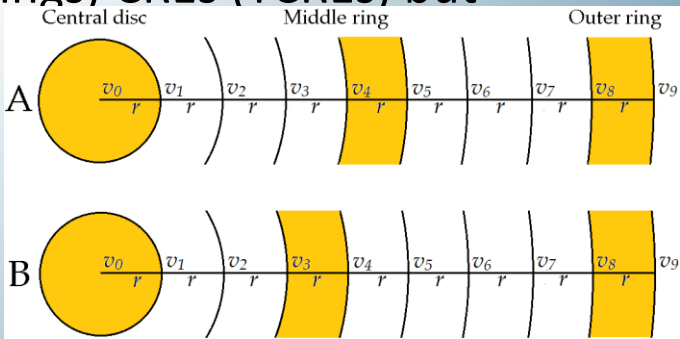


Figure 3. Finite dimensions models (FDMs) of the tripolar (2 rings) concentric ring electrodes (TCREs) from [4]: (A) constant inter-ring distances (CIRD) and (B) linearly increasing inter-ring distances (LIIRD).

Materials and Methods

- FDM comparison framework, allowing direct comparison between two CRE configurations with the same number of rings and the same size but with different radii of the central disc, widths of concentric rings, and inter-ring distances, was validated on human electrocardiogram in [4].

- In this study, this framework has been developed into an optimization problem comparing not pairs but all the possible CRE configurations of the same size and with the same number of rings simultaneously.

- Absolute values of truncation term coefficients for the lowest remaining truncation term order were compared since in [2] and [3] ratios of those coefficients have been shown, using finite element method modeling, to be predictors of the Laplacian estimation error.

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Results

TCRE number	Central disc radius	Middle ring radii		Outer ring radii		Absolute value of the 6th order truncation term coefficient	Increase with respect to the optimal (%)
		Inner	Outer	Inner	Outer		
1	1	2	3	4	6	0.685	0
2	1	2	3	5	6	0.717	4.65
3	1	2	4	5	6	1.096	59.99
4	1	3	4	5	6	1.250	82.53
5	2	3	4	5	6	1.369	99.93

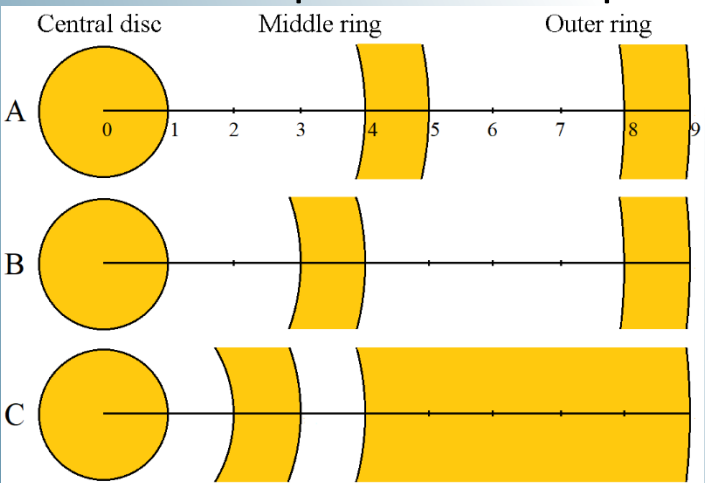
Table 1. All possible tripolar concentric ring electrode (TCRE) configurations for the outer radius of the outer ring equal to 6.

- General principles defining optimal CRE configurations (independent of the number of concentric rings) in terms of accuracy of the surface Laplacian estimate are:
  - In the optimal configuration, central disc and concentric rings are kept at minimum distances with minimum radius/widths except for the width of the outer ring. Example: TCRE configuration number 1 in Table 1.
  - Larger width of the outer ring is advantages to smaller width in electrode configurations that are otherwise identical. Example: TCRE configuration number 1 versus number 2 in Table 1.
  - Increasing the width of a concentric ring closer to the outer edge of the electrode is advantageous to increasing the width of a concentric ring closer to the central disc. Example: TCRE configuration number 2 versus numbers 1 and 3 in Table 1.
  - Increasing the width of any concentric ring is advantageous to increasing the radius of the central disc. Example: TCRE configuration number 1 versus numbers 3 and 5 in Table 1.
  - Increasing the distance between recording surfaces closer to the outer edge is advantageous to increasing the distance between recording surfaces closer to the central disc. Example: TCRE configuration number 2 versus number 4 in Table 1.

Results

- Optimal TCRE configuration (#1 in Table 2; Fig. 4, C) was directly compared to constant inter-ring distances (CIRD; #30 in Table 2; Fig. 4, A) and linearly increasing inter-ring distances (LIIRD; #15 in Table 2; Fig. 4, B) configurations of the same size from [4].

- CIRD corresponds to a more than three-fold increase (213.01%) in Laplacian estimation error while LIIRD configuration corresponds to almost two-fold increase (99.33%) in Laplacian estimation error compared to the optimal TCRE configuration (Table 2).



electrode configurations: (A) constant inter-ring distances (CIRD), (B) linearly increasing inter-ring distances (LIIRD), and (C) optimal configuration with respect to the accuracy of Laplacian estimation.

Table 2. Select tripolar concentric ring electrode (TCRE) configurations for the outer radius of the outer ring equal to 9.

TCRE number	Central disc radius	Middle ring radii		Outer ring radii		Absolute value of the 6th order truncation term coefficient	Increase with respect to the optimal (%)
		Inner	Outer	Inner	Outer		
1	1	2	3	4	9	1.447	0
2	1	2	3	5	9	1.458	0.78
3	1	2	3	6	9	1.489	2.94
4	1	2	3	7	9	1.550	7.19
5	1	2	3	8	9	1.650	14.07
…	…	…	…	…	…	…	…
15	1	3	4	8	9	2.883	99.33
…	…	…	…	…	…	…	…
30	1	4	5	8	9	4.528	213.01
…	…	…	…	…	…	…	…

Discussion

- The distinctive feature of obtained FDM based optimization results is that in optimal CREs (e.g. Fig. 4, C) the recording surfaces account for the vast majority of the electrode surface area minimizing the distances between the recording surfaces.

- This is markedly different from the currently used CREs where majority of the electrode surface area corresponds to the distances between the recording surfaces (e.g., Fig. 2 from [4]).

- These results have potential to inform the design of future CREs and could not have been obtained with simplistic NDM [1-3].

[1] Makeyev O., Ding Q., Besio W., (2016) *Measurement*, 80: 44-52
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Discussion

- The only optimization criterion used in this study was maximizing the accuracy of surface Laplacian estimation via the CRE. Other optimization criteria may result in different optimal CRE configurations.

- The question of how small can the distances between the recording surfaces get before shorting due to salt bridges negatively affects the accuracy of Laplacian estimation becomes more critical than before since the first principle defining optimal configurations is to keep those distances minimal. Prototyping of optimal CRE configurations is needed to answer this question.

- Extended version of this conference paper including confirmation of the analytic results via finite element method modeling will be submitted to the ECSA7 Special Issue of Sensors.

Thank you!