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# Comparing Optimal and Commercially Available Bipolar and Tripolar Concentric Ring Electrode Configurations Using Finite Element Method Modeling Based on Their Finite Dimensions Models

Oleksandr Makeyev, *Senior Member, IEEE*, Yiyao Ye-Lin, Gema Prats-Boluda, *Member, IEEE*, and Javier Garcia-Casado

Diné College
Ci²B
UNIVERSITAT POLITÈCNICA DE VALÈNCIA
NSF

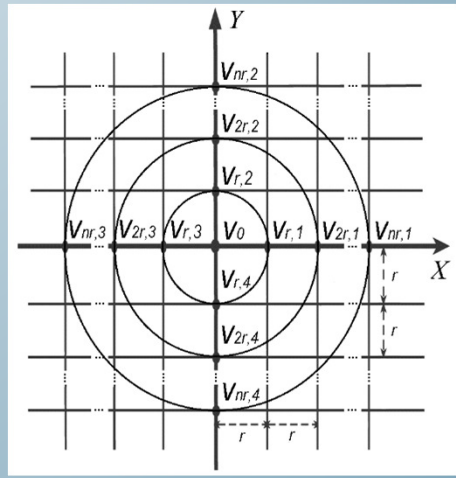
# Introduction

- 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 a concentric ring electrode (CRE) from [2].



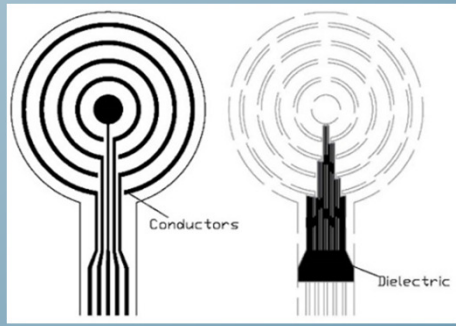




Figure 2. Pentapolar (4 rings) concentric ring electrode (CRE) from [4].


[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.
- In [5] it was solved for tripolar CREs (TCREs) maximizing the accuracy of the surface Laplacian estimation since ability to estimate Laplacian at each electrode constitutes the primary biomedical significance of CREs.

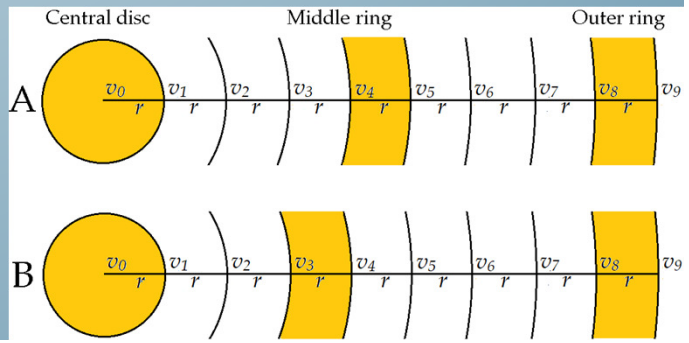



Figure 3. Finite dimensions models (FDMs) of the tripolar (2 rings) concentric ring electrodes (TCREs) from [4]: (A) constant inter-ring distances (CIRD) and (B) linearly increasing inter-ring distances (LIIRD).


[5] Makeyev O. (2020) *ECSA-7* talk

# Introduction

- Optimal TCRE configuration (#1 in Table 1; Fig. 4, C) was directly compared to constant inter-ring distances (CIRD; #30 in Table 1; Fig. 4, A) and linearly increasing inter-ring distances (LIIRD; #15 in Table 1; 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 1) [5].

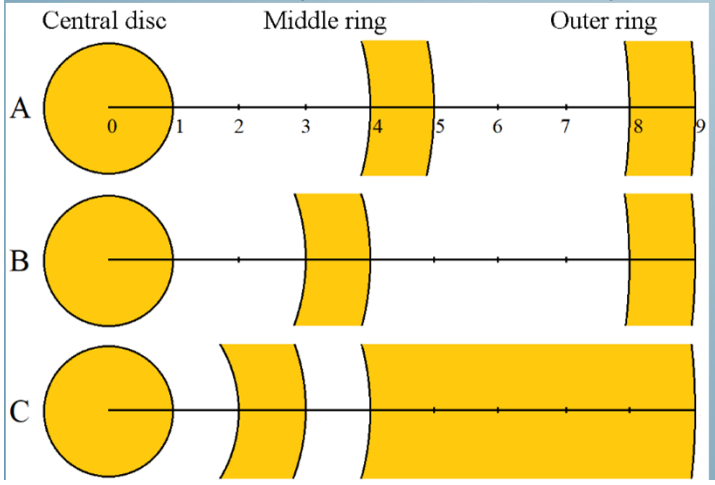



Figure 4. Finite dimensions models (FDMs) of three tripolar concentric ring electrodes (TCREs) including: (A) constant inter-ring distances (CIRD), (B) linearly increasing inter-ring distances (LIIRD), and (C) optimal configuration with respect to the accuracy of Laplacian estimation.

Table 1. 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 |
| … | … | … | … | … | … | … | … |

# Introduction

- For the first time, the NDM based FEM model from [1]–[3] has been adapted to FDM to perform the direct comparison between the three TCRE configurations from [5, 6] (Fig. 5): relative and normalized maximum error ratios of Laplacian estimation (mean ± standard deviation for 10 CRE sizes) computed using the FEM model were equal to 1.97 ± 0.02 and 1.96 ± 0.02 respectively (LIIRD over optimal) as well as 3.07 ± 0.05 and 3.05 ± 0.07 respectively (CIRD over optimal) [6, 7].

- Moreover, FEM results suggested improved sensitivity and spatial resolution with optimal TCRE [6, 7].

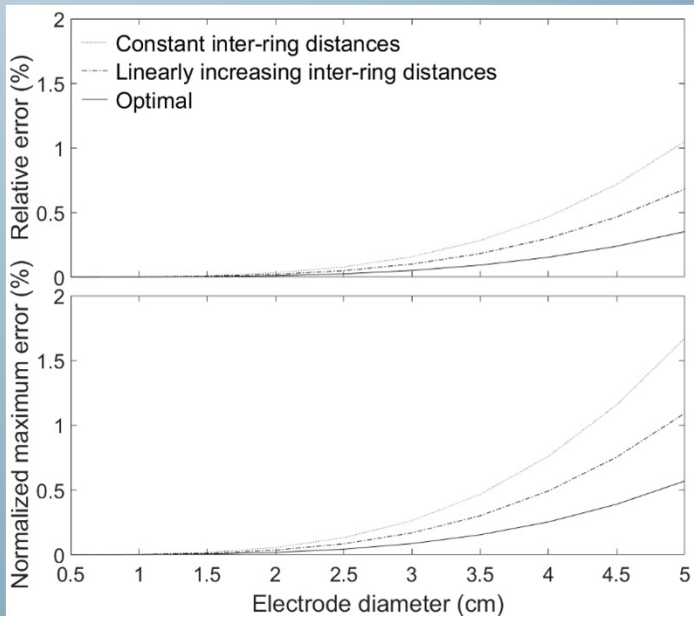



Figure 5. Relative (top) and normalized maximum (bottom) errors of surface Laplacian estimation corresponding to constant inter-ring distances (CIRD), linearly increasing inter-ring distances (LIIRD), and optimal tripolar concentric ring electrode (TCRE) configurations.


[6] Makeyev O., et al. (2021) *Sensors*, 21(17): 5881

[7] Makeyev O., et al. (2021) *43rd IEEE EMBC*, 7244-7247

# Introduction

- In this study, FEM modeling is used to directly compare optimal bipolar CRE (BCRE) and TCRE configurations to bipolar configurations of the same size with dimensions corresponding to the commercially available CoDe® electrodes manufactured by Spes Medica (Genova, Italy).

- Moreover, it also compares BCRE and TCRE configurations of different sizes. In particular, optimal TCRE configuration is compared to a bipolar configuration consisting out of its central disc and middle ring only.

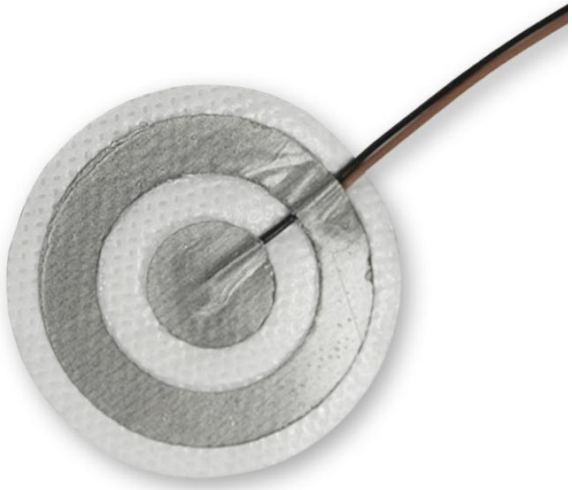


Figure 6. CODE401526 electrode from Spes Medica: GVB-geliMED, "Electrodo adhesivo bipolar (IOM)," GVB-SPES ES. https://www.gvb-spes.es/accesorios-de-iom/iom-electrodos-de-neurocirugia/329/electrodo-adhesivo-bipolar-iom (accessed Jan. 18, 2022)

# Methods

- CRE configurations (Fig. 7):
  - Specific CoDe® models included: CODE401526 with 40 mm diameter and CODE501526 with 50 mm diameter.
  - For CODE401526 with internal and external diameters of the outer ring equal to 20 mm and 30 mm respectively and the diameter of the central disc equal to 10 mm scaling its dimensions to the size of the optimal TCRE configuration from [5-7] with outer radius subdivided into 9 equal intervals (Fig. 7D) results in FDM from Fig. 7B while scaling it to a one third of its size results in FDM from Fig. 7A which is also equivalent to just the central disc and middle ring only of the optimal TCRE from Fig. 7D.
  - CODE501526 with internal and external diameters of the outer ring equal to 30 mm and 42 mm respectively and the diameter of the central disc equal to 16 mm with rounding to the nearest integer also gives BCRE from Fig. 7B.
  - Optimal BCRE from Fig. 7C stems directly from the first general principle defining optimal CRE configurations in [5,6].

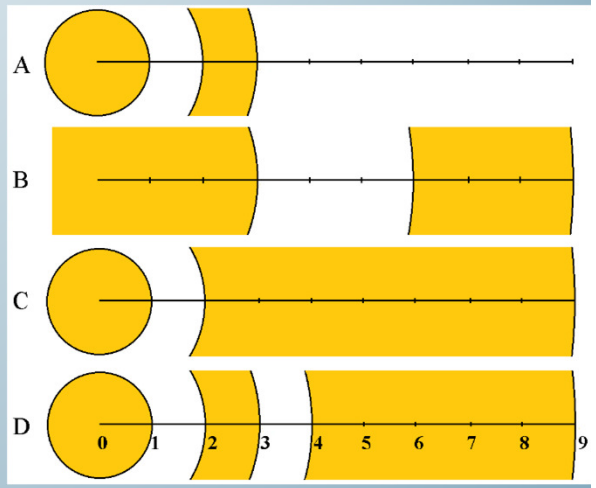



Figure 7. Finite dimensions models (FDMs) of three bipolar and one tripolar concentric ring electrode (CRE) configurations including: small (A), large (B), and optimal (C) bipolar configurations as well as optimal (D) tripolar configuration with respect to the accuracy of Laplacian estimation.

# Methods

- FDM based FEM model (Fig. 8):
  - evenly spaced mesh size of 700 x 700 corresponding to roughly 20 x 20 cm was located in the first quadrant of the *X*-*Y* plane over a dipole projected to the center of the mesh and oriented towards the positive direction of the *Z* axis;
  - At each point of the mesh, the electric potential was generated by a unit charge dipole at 5 cm depth;
  - The analytical Laplacian was then computed at each point of the mesh, by taking the second derivative of the electric potential;
  - Laplacian estimates for four CRE configurations from Fig. 7were computed at each point of the mesh where appropriate boundary conditions could be applied for diameters ranging from 0.5 cm to 5 cm;
  - These four Laplacian estimates were compared with the calculated analytical Laplacian for each point of the mesh, where corresponding Laplacian estimates were computed, using relative error and normalized maximum error measures.

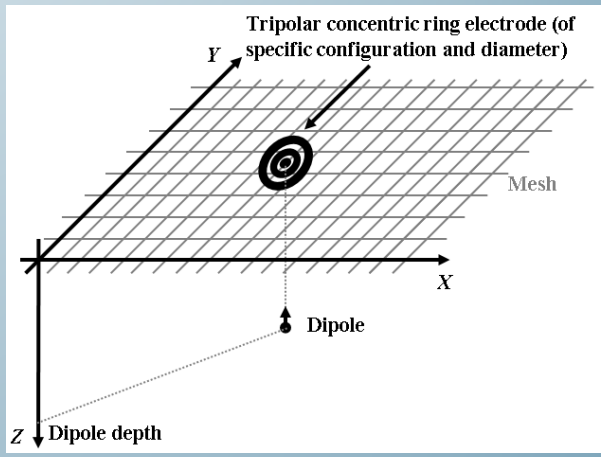



Figure 8. Schematic of the finite element method (FEM) model used to compare Laplacian estimates.

$$\text{Relative error}^i = \sqrt{\frac{\sum (\Delta v - \Delta^i v)^2}{\sum (\Delta v)^2}}$$

$$\text{Normalized maximum error}^i = \frac{\max\left|\Delta v - \Delta^i v\right|}{\max\left|\Delta v\right|}$$

# Results

- Relative and normalized maximum errors on semi-log scale (Fig. 9):
  - Compared to the optimal TCRE configuration from Fig. 7D, commercially available BCRE of the same size from Fig. 7B corresponds to a median increase in Laplacian estimation error (ratios of respective errors obtained for 10 CRE sizes) of 146 (relative error) and 120 (normalized maximum error) times while its counterpart one third of its size from Fig. 7A corresponds to an increase of 18.45 (relative error) and 15.45 (normalized maximum error) times.
  - Compared to the optimal BCRE configuration from Fig. 7C, commercially available BCRE of the same size from Fig. 7B corresponds to a median increase in Laplacian estimation errors of 1.2 times (both relative and normalized maximum errors).
  - While latter is negligible for practical applications, the importance of the former is discussed below.
  - These results are consistent with previous (and NDM based) BRCE versus TCRE comparisons [1-3].

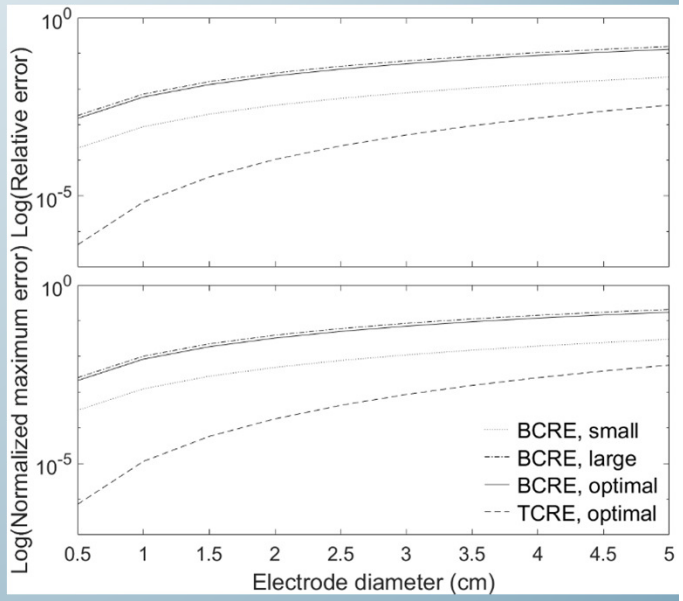



Figure 9. Relative (top) and normalized maximum (bottom) errors of surface Laplacian estimation corresponding to four concentric ring electrode (CRE) configurations presented on a semi-log scale.

# Results

- Relative and normalized maximum errors on linear scale (Fig. 10):
  - Two most relevant CRE sizes out of the 10 sizes total included in this study are CRE diameters of 3 cm (identical to CODE401526) and 4 cm (closest to CODE501526).
  - For the 3 cm diameter commercial BCRE from Fig. 7B corresponds to the Laplacian estimation errors of 6.15% (relative error) and 8.45% (normalized maximum error) while optimal TCRE from Fig. 7D of the same size allows decreasing these errors to 0.05% and 0.09% respectively.
  - For the 4 cm diameter commercial BCRE from Fig. 7B corresponds to the Laplacian estimation errors of 10.49% (relative error) and 14.15% (normalized maximum error) while optimal TCRE from Fig. 7D of the same size allows decreasing these errors to 0.15% and 0.25% respectively.

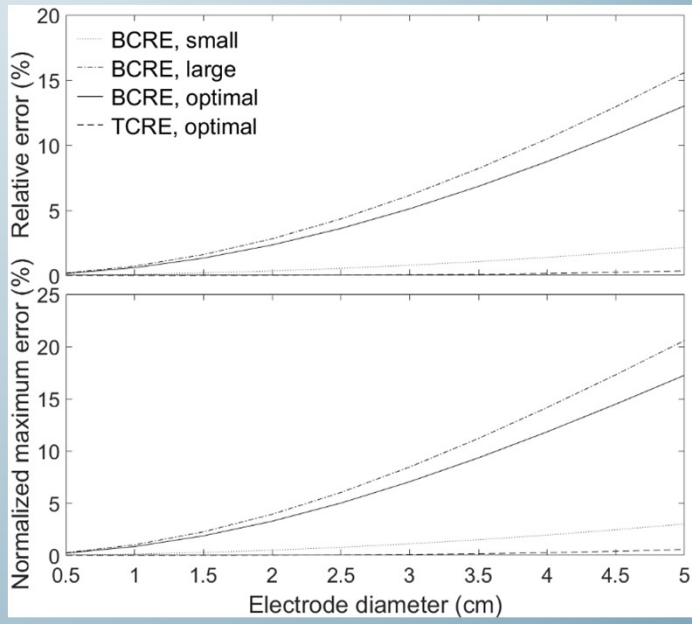



Figure 10. Relative (top) and normalized maximum (bottom) errors of surface Laplacian estimation corresponding to four concentric ring electrode (CRE) configurations presented on a linear scale.

# Discussion

- This study represents the first attempt to directly compare optimal BCRE and TCRE configurations from Fig. 7C-D to their commercially available counterparts in terms of the accuracy of the surface Laplacian estimation using FDM based FEM modeling.

- Quantifying the difference between optimal and commercially available configurations could provide an insight to incorporate into the design of future CREs for real-life applications not limited to the ones that already rely on commercially available CREs.

- Next step would be to add TCRE with dimensions corresponding to t-Lead electrodes (CREmedical, Kingston, RI, USA). Measures quantifying sensitivity and spatial resolution as in [6] will also be added for all the CRE configurations included.

Thank you!