Recent Progress in Design Optimization of Concentric Ring Electrodes Based on Negligible and Finite Dimensions Models

Oleksandr Makeyev

Diné College, Tsaile, AZ

Abstract

This poster reports on the recent progress in both negligible and finite dimensions models based optimization of concentric ring electrode design maximizing the accuracy of the surface Laplacian estimate signal.

Introduction

Concentric ring electrodes (CREs; tripolar configuration presented in Fig. 1B) are noninvasive and wearable sensors for electrophysiological measurement uniquely capable of estimating the surface Laplacian (second spatial derivative of surface potential) at each electrode as opposed to the conventional disc electrodes (Fig. 1A) which constitutes their primary biomedical significance. Therefore, optimization of CRE design is an important problem since its criterion is maximization of the Laplacian estimation accuracy. Two CRE models currently used for such optimization are the negligible dimensions model (NDM) [1] and the finite dimensions model (FDM) [2-4]. While realistic FDM allows comprehensive optimization where all of the electrode parameters including the radius of the central disc and individual widths of concentric rings (all of them considered negligible in simplistic NDM) are optimized simultaneously, it also increases the number of decision variables making optimization problem more complex.

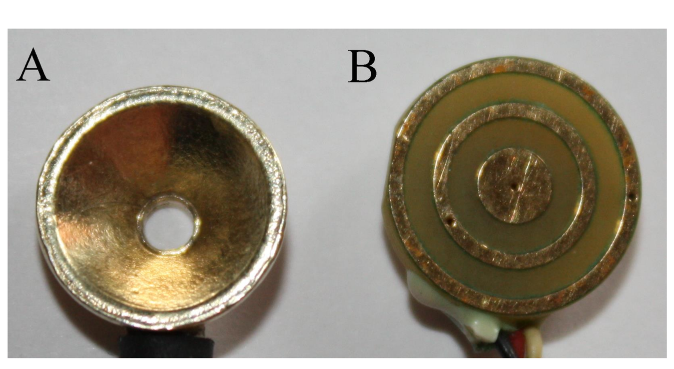


Figure 1 (left). Conventional disc electrode (A) and tripolar CRE configuration (B).

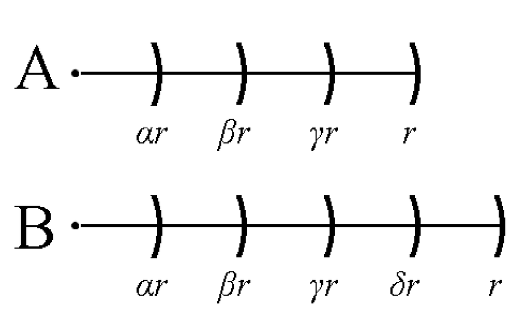
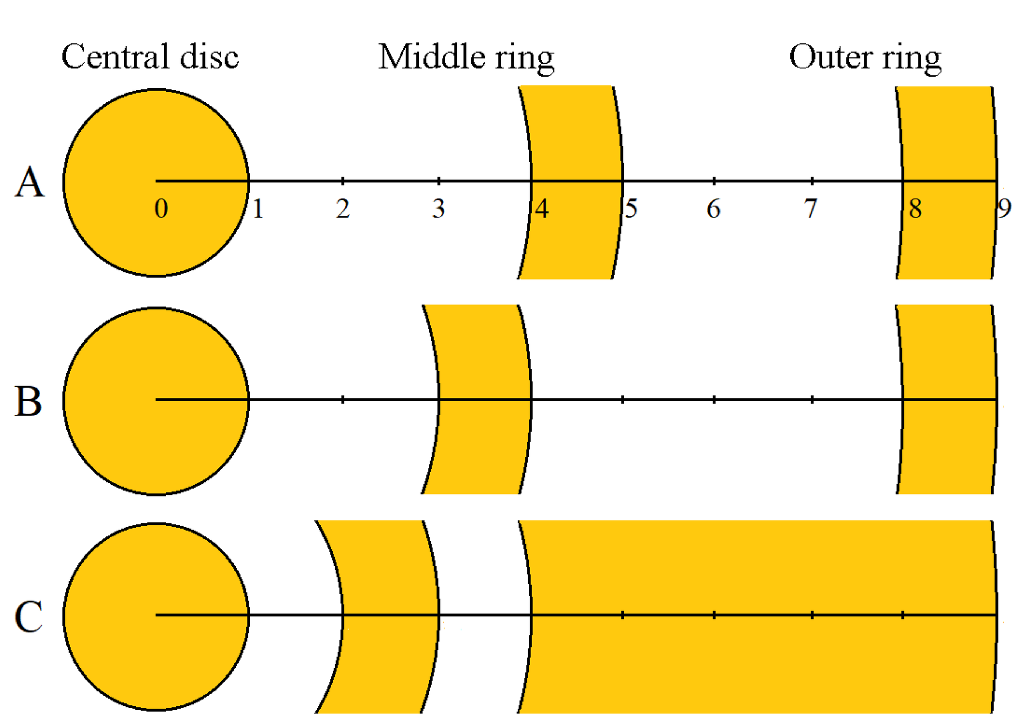


Figure 2 (right). NDMs of pentapolar (A) and sextopolar (B) CRE configurations.



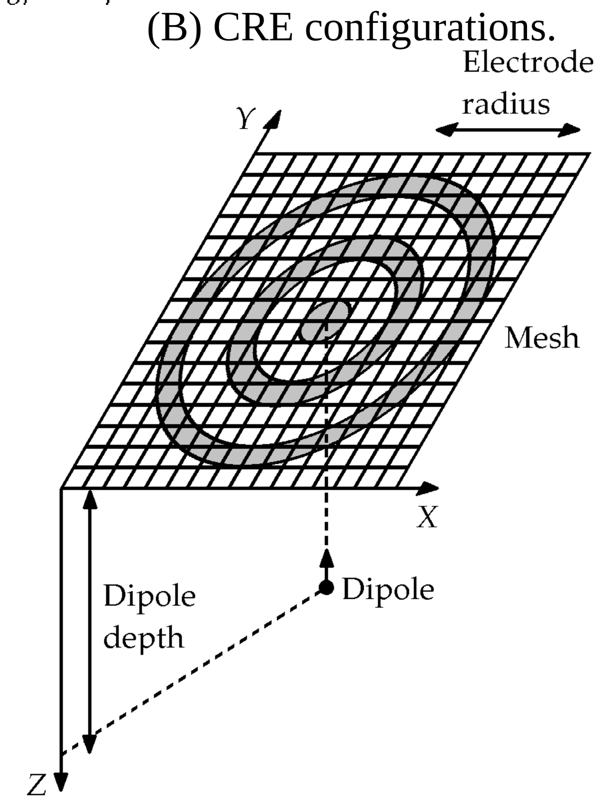


Figure 3 (top left). FDMs of constant (A) and linearly increasing (B) inter-ring distances and optimal (C) tripolar CRE configurations.

Figure 4 (top right). FDM based FEM model.

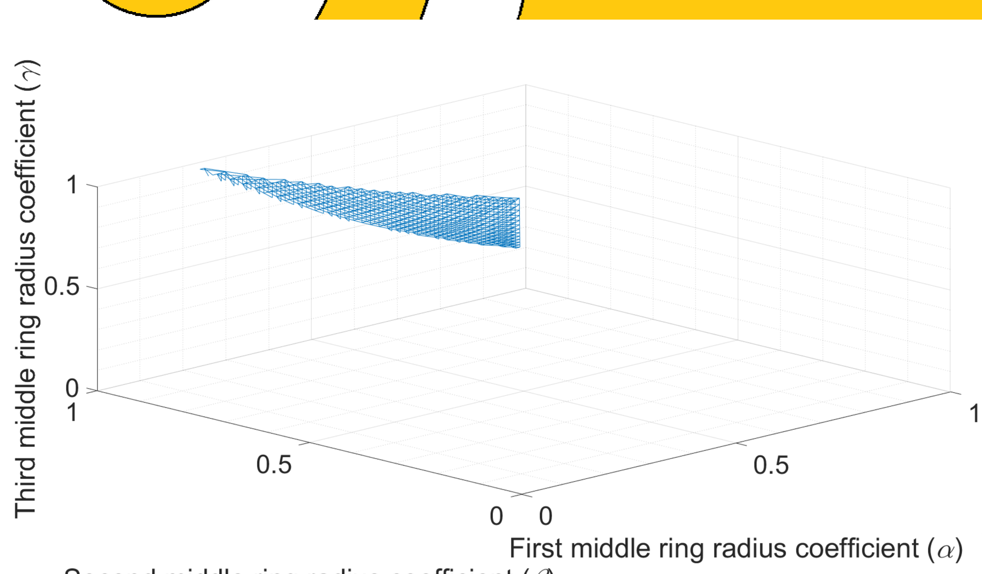


Figure 5 (bottom left). 5th percentile fitted boundary hyperplane for pentapolar CRE.

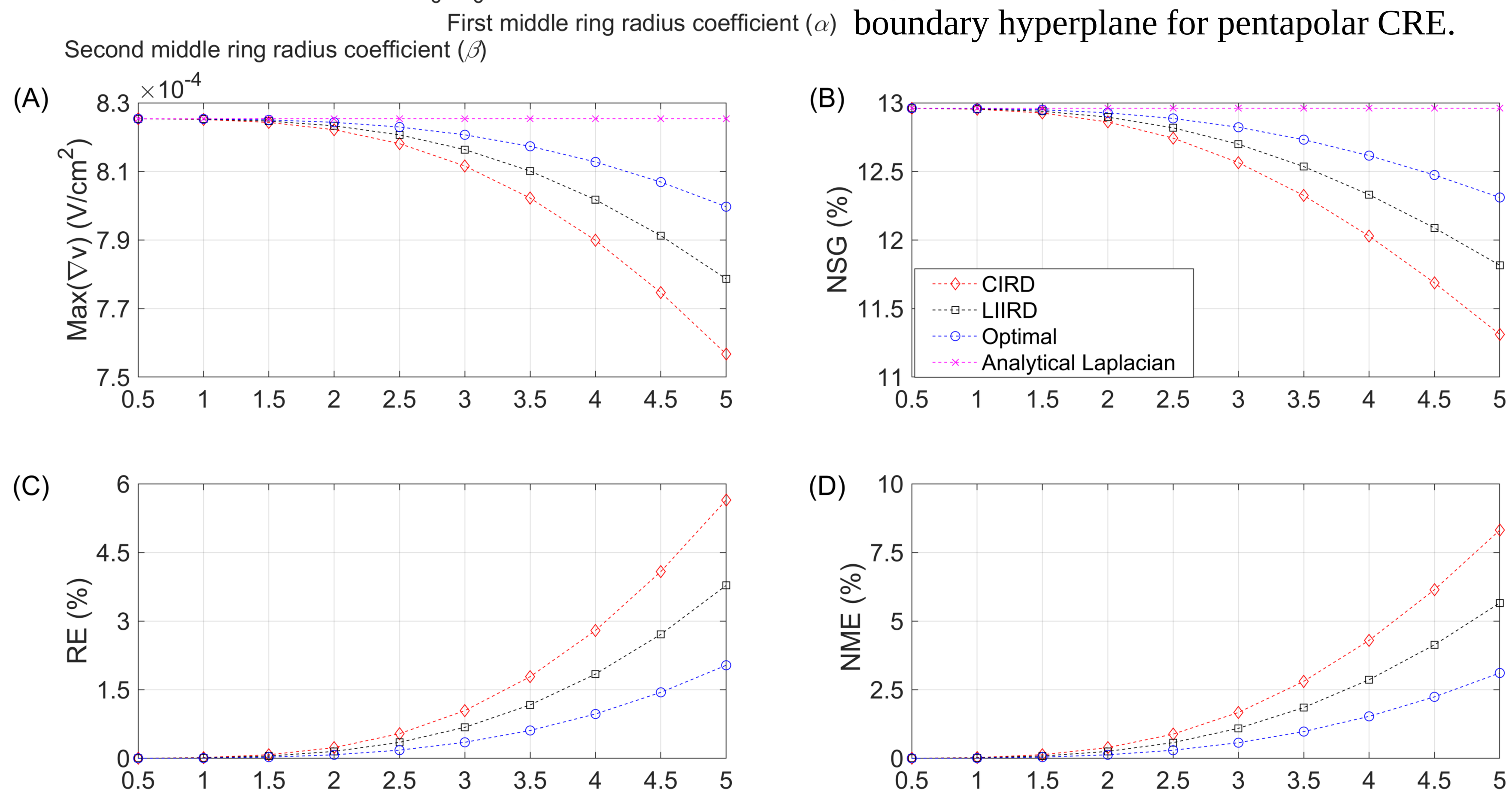


Figure 6 (top). Maximum Laplacian amplitude (A), normalized spatial gradient (B), and relative (C) and normalized maximum (D) errors of Laplacian estimation computed via FEM modeling for tripolar CREs.

Methods

For the NDM based inter-ring distances optimization, the optimization problem has been solved for pentapolar (4 concentric rings; Fig. 2A) and sextopolar (5 rings; Fig. 2B) CRE configurations using a wide range of truncation error percentiles ranging from 1st to 25th [1].

For the comprehensive FDM based optimization, general principles defining optimal CRE designs have been derived and illustrated on tripolar (2 rings) CRE configuration. For tripolar CREs, the optimal configuration (Fig. 3C) was directly compared to previously proposed and FDM based linearly increasing inter-ring distances (Fig. 3B) and constant inter-ring distances (Fig. 3A) tripolar CRE configurations of the same size [2, 3]. Moreover, all the analytic results have been confirmed using finite element method modeling (Fig. 4) adapted from NDM to FDM for the first time [3, 4].

Results

For the NDM based inter-ring distances optimization, for example, for the 5th percentile, optimal range of values of α, β and γ for the pentapolar CRE configuration with middle rings radii equal to αr, βr and γr and outer ring radius of r such that $0 < \alpha < \beta < \gamma < 1$ is determined by inequality $\alpha\beta\gamma \leq 0.213$ (Fig. 5) [1]. Respective optimal range of values of α, β, γ and δ for the sextopolar CRE configuration with an additional middle ring of radius δr such that $0 < \alpha < \beta < \gamma < \delta < 1$ is determined by inequality $\alpha\beta\gamma\delta \leq 0.204$ [1]. Obtained results also confirmed consistency between the optimal ranges for all the CRE configurations with up to 5 rings that may allow estimation of optimal ranges for CRE configurations with 6 rings or more at which point optimization problem becomes prohibitively computationally intensive to solve directly [1].

For the comprehensive FDM based optimization, obtained results suggest that previously proposed configurations correspond to an almost two-fold and more than three-fold increases in Laplacian estimation error respectively compared to the optimal tripolar CRE configuration (Fig. 6C-D) [2, 3]. Moreover, besides confirming the aforementioned analytical results, finite element method modeling also suggested that optimal tripolar CRE configuration may offer improved sensitivity (Fig. 6A) and spatial resolution (Fig. 6B) further proving its potential [3, 4].

Discussion

Clinical relevance of these NDM and FDM based results is that they may inform future CRE designs. Especially so, for CRE configurations with large numbers of concentric rings which is crucial since accuracy of surface Laplacian estimation has been previously shown to increase with an increase in the number of rings.

References

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