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Electrochemical Characterization of Commercially Pure Titanium Electrodes for Orthopaedic Applications: A Re-evaluation of Electric Field Models

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INTRODUCTION & AIMS

Titanium and its alloys are extensively used in orthopaedic applications due to their excellent mechanical properties, biocompatibility, and corrosion resistance[1]. Direct electrical stimulation (DES) has also been demonstrated to increase rates of successful fusion in pre-clinical and clinical trials for spinal fusion surgery[2]. For example, in one pilot ovine study, DES via titanium electrodes was shown to reduce the overall time to fusion as well as enhance fusion quality[3].

However, titanium is not often the material of choice for electrically stimulating bioelectrodes, especially as both the cathode and anode. As such, they have not been extensively characterized.

Furthermore, electric field (EF) strengths have been historically overestimated due to incorrect assumptions on the current distribution processes involved[4]. Along with ambiguous reporting standards, this makes it a challenge to draw definitive conclusions about DES-activated cellular mechanisms of action.

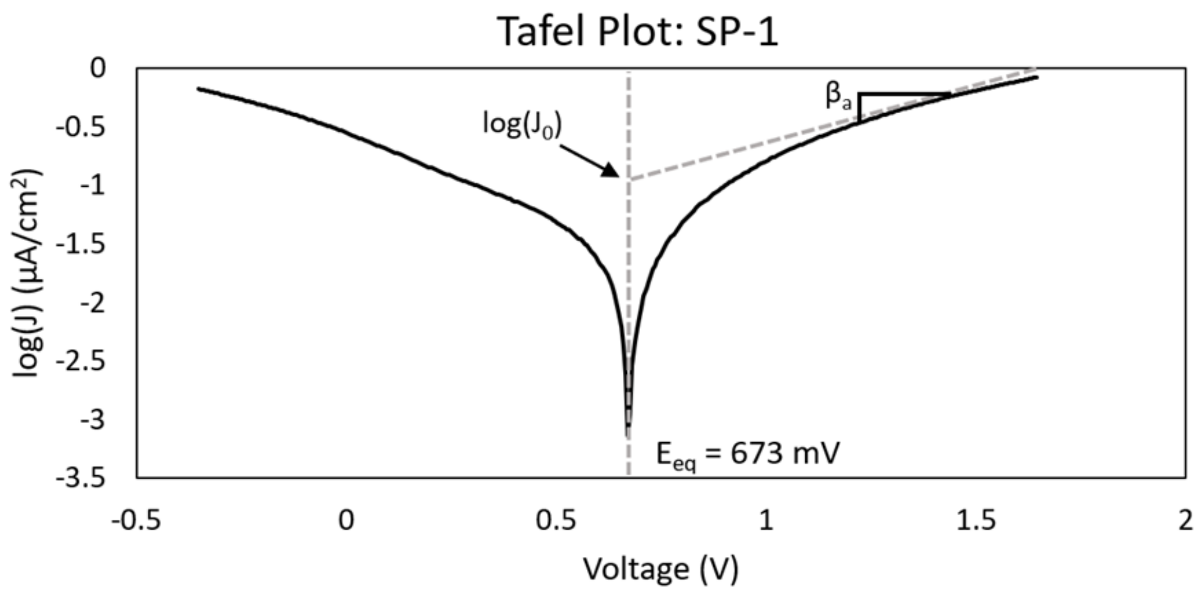
Study Aims:

- Characterize the effects of anodization voltage and oxide layer configuration on EF distribution under voltage-controlled constant DES for commercially pure titanium electrodes.
- Re-evaluate current distribution frameworks for estimating EFs using computational modeling.
- Investigate the role of electrode geometry and spacing on EF uniformity.

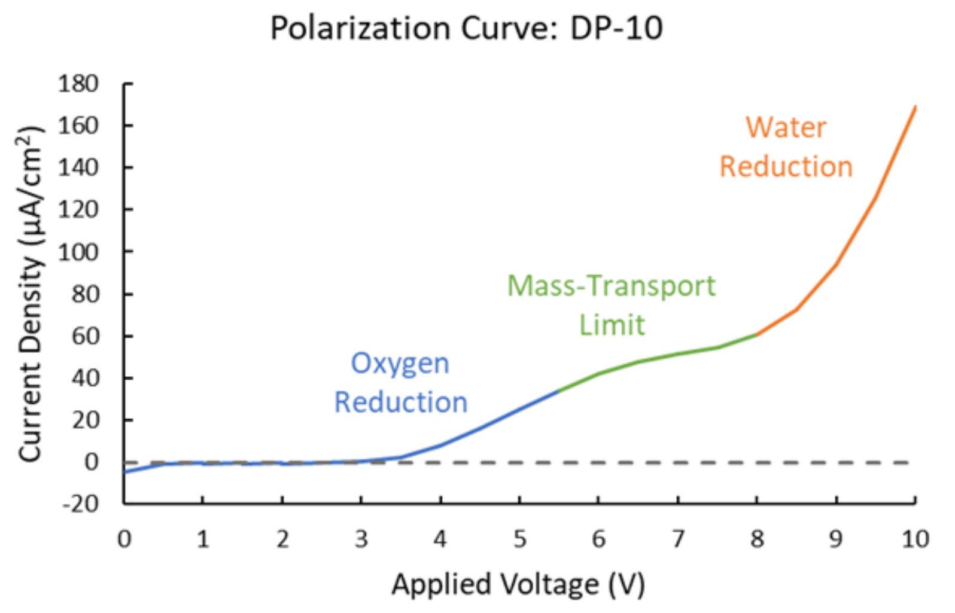
METHODS

Current Distribution Frameworks:

- *Primary Current Distribution (PCD)*
  Ohm's Law → $J = \sigma E$
- *Secondary Current Distribution (SCD)*
  Butler-Volmer Approximation → $\left\{ \begin{array}{c} J_{loc} = J_0 * 10^{\eta/\beta_a} \\ J_{loc} = -J_0 * 10^{\eta/\beta_c} \end{array} \right\}$

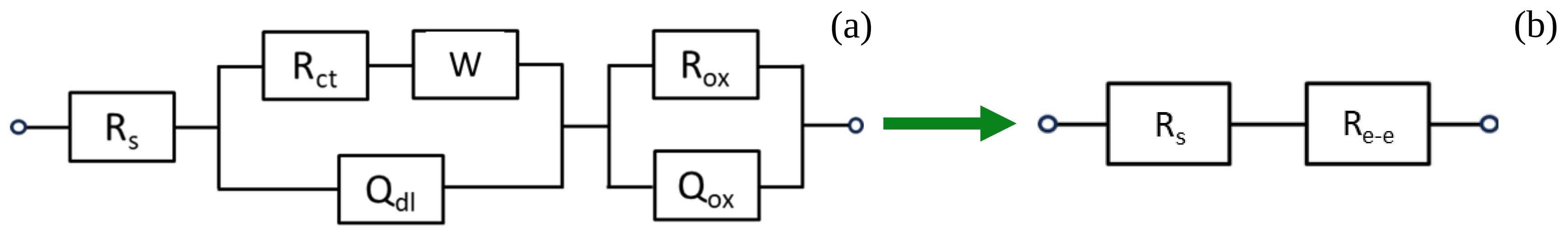


Tafel plot used to determine the Butler-Volmer coefficients. Scan rate of 1.1 mV/sec at the open circuit potential (OCP)± 1V.



Polarization curve used to identify secondary reactions and diffusion limitations in the 10 V chambers.

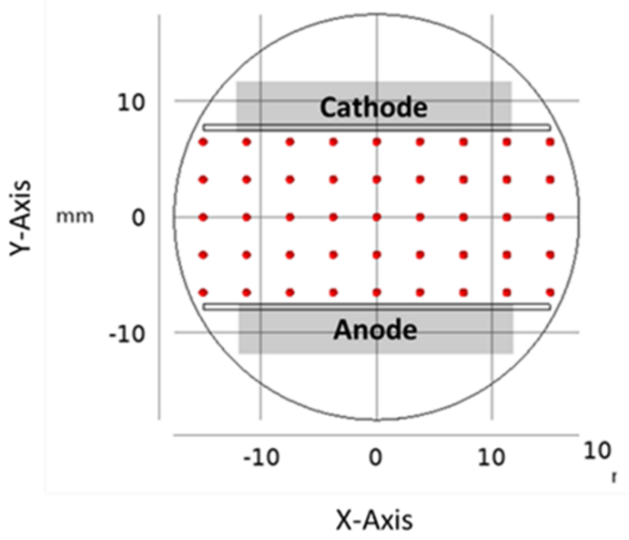
- *Pseudo-Tertiary Current Distribution (P-TCD)*
  Lumped-Parameter Model + Ohm's Law



(a) General equivalent electric circuit for the DES chambers. Rs is the solution resistance, R_{ct} is the charge transfer resistance, W is the Warburg impedance, Q_{dl} is the constant phase element representing the electric double layer, R_{ox} is the oxide layer resistance, and Q_{ox} is the constant phase element representing the oxide layer. (b) Simplified circuit under constant voltage where $R_{e\text{-}e}$ is the bulk resistance across the electrode-electrolyte interface.

Uniform Electric Field Assumption:

- Electrode Area >> Electrode Spacing
- Homogenous Ionic Concentrations

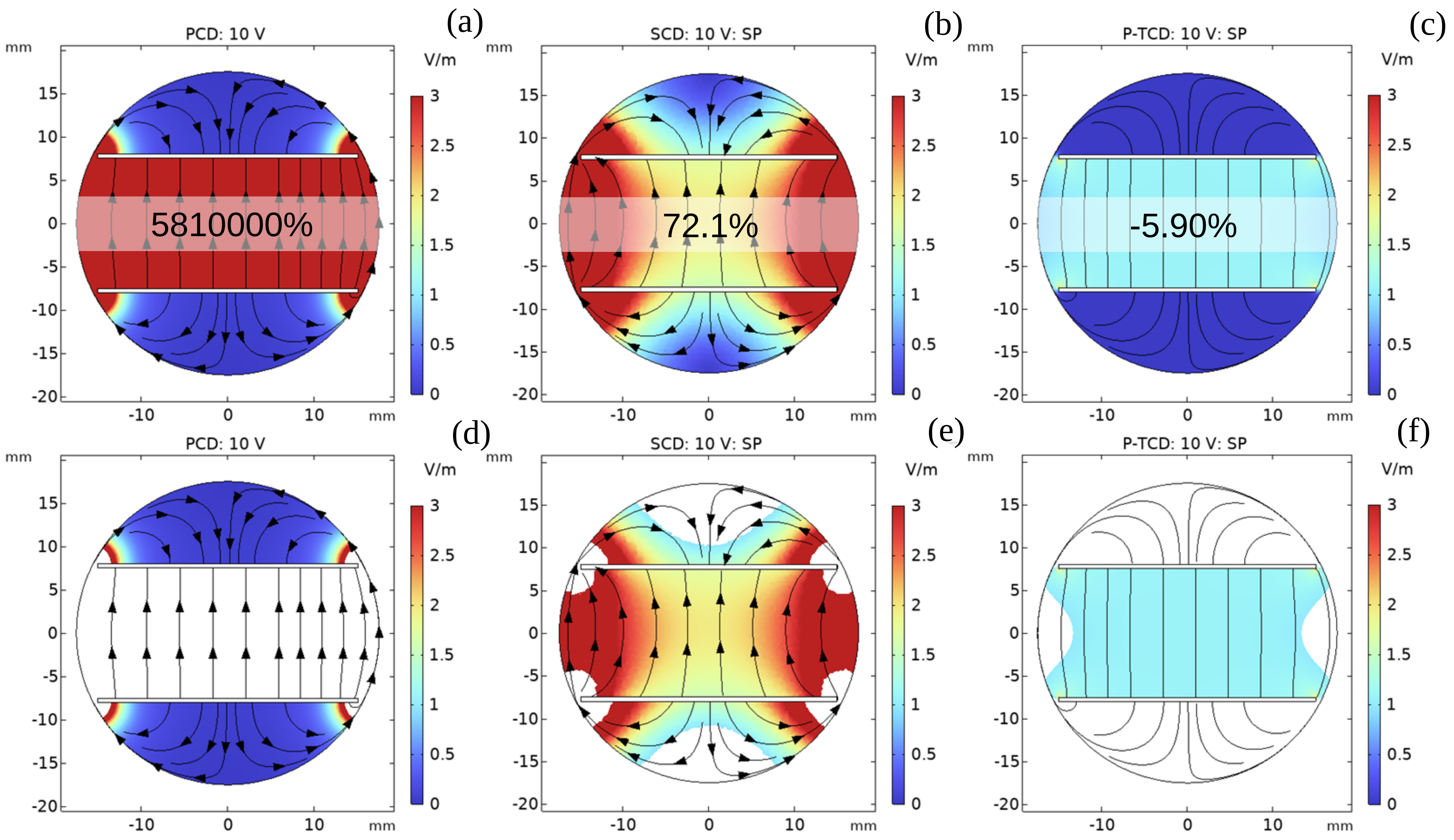


2D grid used to calculated the EF and compare to the center for uniformity.

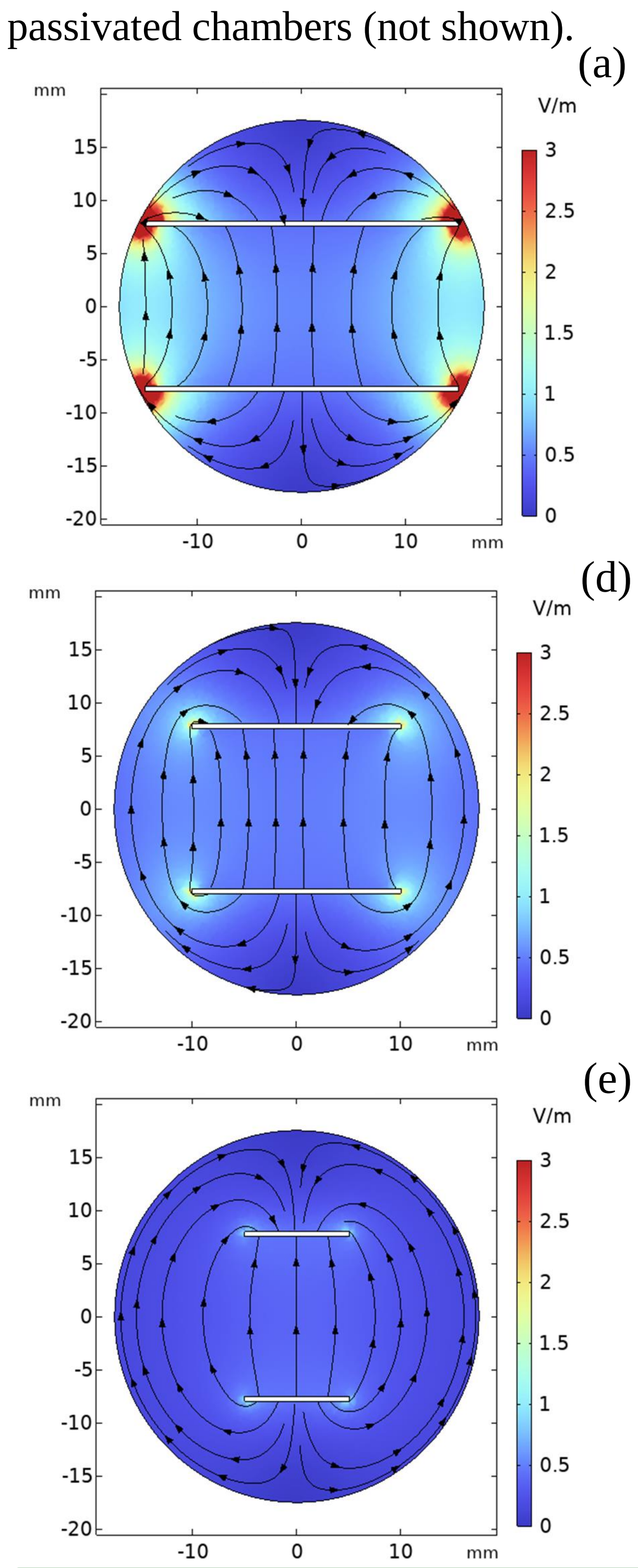
Validation:

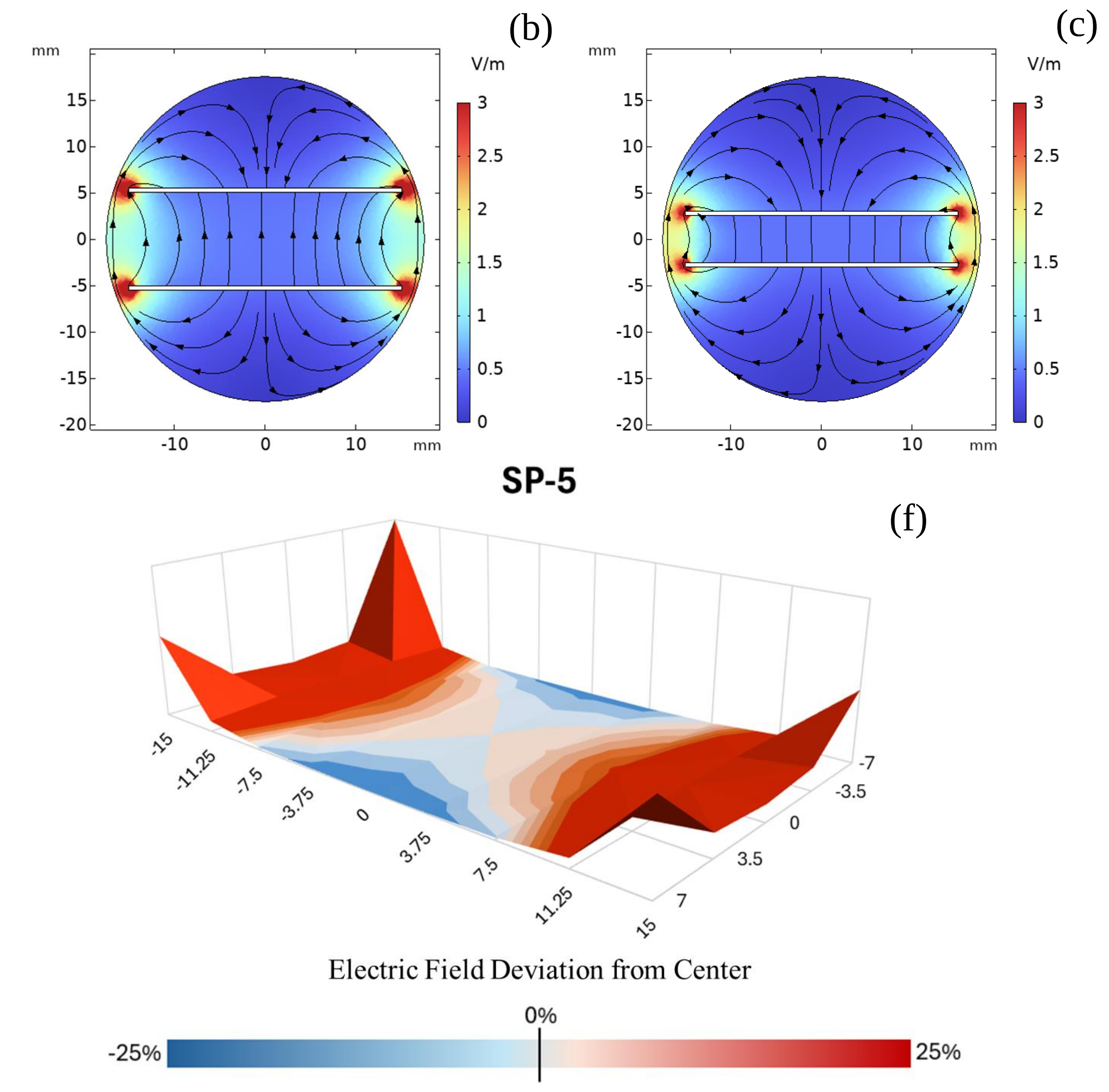
- Empirical data was collected by measuring the voltage across a shunt resistor. The calculated current was used to determine the experimental EF via COMSOL Multiphysics.

RESULTS & DISCUSSION



(a-c) Representative EF distributions for the 10 V single passivated chambers created in COMSOL Multiphysics for the PCD, SCD, and P-TCD frameworks, respectively. Percent deviation from experimental values highlighted in the center. (d-f) Zones within the EF distribution that are within physiological levels (1-5 V/m)[5]. Double passivated chambers exhibited a -48.97 ± 25.91% decrease in EF compared to single passivated chambers (not shown).





(a-e) EF distributions for the 5 V, single passivated, SCD chamber that compare the effects of electrode length (30, 20, and 10 mm) and electrode spacing (15, 10, and 5 mm) on the uniformity. (f) 3D mapping of the 30/15 mm (length/spacing) chamber highlighting the relative zones of uniformity and intense peaks near the electrode corners.

CONCLUSION

- PCD framework for constant voltage-controlled DES drastically overestimates the EF.
- SCD framework can only accurately predict EFs when diffusion limitations are well defined.
- P-TCD framework accurately predicted EFs within ± 20% across all voltages.
- For the uniform electric field assumption to hold true, the electrode corners should ideally be some distance away from the chamber walls.

FUTURE WORK / REFERENCES

Future work will include model validation with targeted in vitro cell studies, as well as similar characterization for dynamic DES signals, such as monophasic square waves.

References

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