

## SUPPLEMENTARY MATERIAL

**Electrochemical system model:** We provide a detailed analysis of our computational model for predicting temperature elevations due to an applied AC signal. Because CSF is an ionic conductor, we chose an electrochemical system model with ionic compositions given in Table I. Diffusion coefficients at 298K are used from literature [1], [2], they are assumed to be constant because expected temperature elevations are moderate. We also consider the behavior of the electrode-electrolyte interface, which is the site of electrochemical reactions caused by the applied electrical signal.

Table I  
CHEMICAL SPECIES PARAMETERS [69], [70]

Species	Initial Conc. (M)	Diffusion Coeff. ( $10^9 \text{ m}^2/\text{s}$ )*	Mobility ( $10^{-7} \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ )
H <sup>+</sup>	4E-8	9.311	3.486
OH <sup>-</sup>	2.5E-7	5.273	1.974
Cl <sup>-</sup>	0.145	2.032	0.760
Na <sup>+</sup>	0.145	2.032	0.760
H <sub>2</sub> O	55.55(Excess)	-	-

\* Diffusion coefficients at 298 K are used as the closest available in literature for our model temperature of 310K

A transient simulation was performed over 1 cycle (2μs) of the applied waveform (f = 500 kHz) to determine the ionic motion in CSF in response to the changing potential at the electrodes. The transient step solves the Nernst-Plank formulation (S2-S5), which is valid for dilute solutions and is performed on the fluid domain to predict the transport of ionic species under the influence of a time-varying alternating signal (S1)

$$V_{\text{electrode}} = V_0 \cdot \sin(\omega t) \quad (\text{S1})$$

where  $V_0$  is the amplitude (10V) and  $\omega$  is the angular frequency of the applied signal. The Nernst-Plank equations are given in (S2-S5):

$$\frac{\partial c_i}{\partial t} + \vec{\nabla} \cdot \vec{J}_i = 0 \quad (\text{S2})$$

$$\vec{J}_i = -D_i \vec{\nabla} c_i - z_i \mu_i F c_i \vec{\nabla} V(\vec{x}) + \vec{u} \cdot \vec{\nabla} c_i \quad (\text{S3})$$

$$\vec{\nabla} \cdot \sum_i z_i F \vec{J}_i = 0 \quad (\text{S4})$$

$$\sum_i z_i \cdot c_i = 0 \quad (\text{S5})$$

Here, for each ion  $i$ ,  $c_i$  is the concentration,  $D_i$  is the Diffusion coefficient ( $\text{m}^2\text{s}^{-1}$ ),  $z_i$  is the charge number,  $z_i$  is the charge number.  $\mu_i$  is the ionic mobility ( $\text{m}^2\text{s}^{-1}\text{V}^{-1}$ ),  $F$  is Faraday's constant ( $96500\text{Cmol}^{-1}$ ), and  $\vec{J}_i$  is the ionic flux.  $\sum_i z_i F \vec{J}_i$  summed over all ions in CSF is equal to the electrolyte current density.  $V(\vec{x})$  is the potential at position vector  $\vec{x}$ , and  $\vec{u}$  is the velocity vector of the bulk fluid. (S2) indicates the conservation of mass in the system, (S3) is the net sum of fluxes including diffusion and migration, (S4) represents the conservation of charge and (S5) denotes that electroneutrality is upheld in the system. Since the bulk fluid is assumed to be stationary

TABLE II

ELECTROCHEMICAL REACTION PARAMETERS [70]

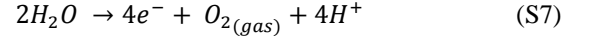
PARAMETER	O.E.R	H.E.R
$\alpha_A$	1.0	2.57
$\alpha_C$	0.1	2.57
$i_0[\text{Am}^{-2}]$	1.4E-3	10

( $\vec{u} = 0$ ), fluid convection does not influence ionic transport and are therefore neglected. The mobility of a species  $i$  is given by the Nernst-Einstein relation

$$\mu_i = D_i \cdot F / R \cdot T \quad (\text{S6})$$

where  $R$  is the ideal gas constant ( $8.314 \text{ Jmol}^{-1}\text{K}^{-1}$ ) and  $T$  is the temperature in K.

**Interfacial electrochemical reactions:** Water is the most abundant molecule in our system. Due to the *overpotential* at the electrodes, water hydrolyses to hydrogen and oxygen gas. The reaction at the anode (+electrode) is known as the Oxygen Evolution Reaction (O.E.R) according to (S7):

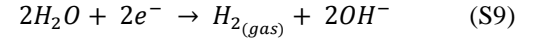


with a standard equilibrium potential of 1.23V [71]. The equilibrium potential is pH dependent and is varies based on the  $\text{H}^+$  concentration according to (S8)

$$E_0 = E_0^{\text{std}} - \frac{2.303RT}{nF} \text{pH} \quad (\text{S8})$$

Here,  $E_0^{\text{std}}$  is 1.23V and  $n$  is the stoichiometric coefficient of the reaction.

At the cathode, the reaction is termed the Hydrogen Evolution Reaction (H.E.R). If the medium is neutral or alkaline pH, water is reduced to yield hydrogen gas and hydroxide ions, which has a standard equilibrium potential of -0.83V and is given in (S9):

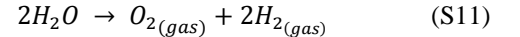


$E_0$  varies according to  $\text{OH}^-$  concentration and is therefore, again pH dependent given by (A10) with  $E_0^{\text{std}}$  is -0.83V [71].

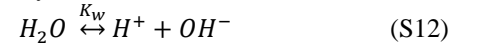
$$E_0 = E_0^{\text{std}} + \frac{2.303RT}{nF} \text{pOH} \quad (\text{S10})$$

Since we use an AC signal, the role of anode and cathode are switched in the second half of the cycle.

The net reaction of hydrolysis in the system is obtained by adding (S7) and (S9).



Additionally, the equilibrium between  $\text{H}^+$  and  $\text{OH}^-$  concentration is given by the dissociation of water as in (S12)



where the ionic product  $K_w$  is  $10^{-14}$ . The electrical current generated at the electrode because of the overpotential  $\eta$  is given by the Butler-Volmer equation shown in (S13).

$$i_{rxn} = i_0 \cdot (e^{\alpha_a F \eta / RT} - e^{-\alpha_c F \eta / RT}) \quad (\text{S13})$$

Here,  $i_{rxn}$  is the current density in  $\text{Am}^{-2}$ ,  $\eta$  is the overpotential at the electrode,  $i_0$  is the equilibrium current density for the electrochemical reaction occurring at the electrode,  $T$  is the temperature in Kelvins,  $\alpha_a$  and  $\alpha_c$  are the anodic and cathodic coefficients that quantify the symmetry of the equilibrium electrochemical reactions occurring at the electrode surface. Electrochemical reaction parameters for both O.E.R and H.E.R are provided in Table II.

The overpotential  $\eta$  at the interface is defined as

$$\eta = V_{\text{electrode}} - V_{\text{electrolyte}} - E_0 \quad (\text{S14})$$

where  $V_{\text{electrode}}$  is the externally applied potential,  $V_{\text{electrolyte}}$  is the potential in the electrolyte next to the electrode and  $E_0$  is the equilibrium potential for the species reaction. In addition to this reaction current, a capacitive current due to the interfacial double layer is also present, given in (S15).

$$i_{\text{cap}} = C_{\text{dl}} \cdot \frac{dV_{\text{electrode}}}{dt} \quad (\text{S15})$$

$C_{dl}$  is the double layer specific capacitance ( $\text{Fm}^{-2}$ ). The electrochemical parameters for hydrolysis are obtained from literature [70]. The total capacitance of the electrodes was measured to be 8.9 nF using electrochemical impedance spectroscopy. The net current at the electrode is the sum of these two components

$$I_{total} = A_{elec} \cdot (i_{rxn} + i_{cap}) \quad (\text{S16})$$

$A_{elec}$  is the surface area of the electrode. This system of equations (S1-S16) is solved over a complete cycle of the waveform (2 $\mu\text{s}$ ) to determine the ionic current density profile in the electrolyte i.e. CSF.

TABLE III

MATERIAL PROPERTIES USED FOR COMPUTATIONAL SIMULATIONS

Parameter	CSF	Silicone	Brain Tissue	Blood
k ( $\text{W/m}\cdot\text{K}$ )	0.61	0.25	0.52	-
$\rho$ ( $\text{kg/m}^3$ )	-	-	1079	1057
$C_p$ ( $\text{J/kg}\cdot\text{K}$ )	-	-	-	3600
$w_t$ ( $\text{ml/s/cm}^3$ )	-	-	0.01	-

k is the thermal conductivity,  $\rho$  is the density,  $\epsilon_r$  is the relative permittivity,  $C_p$  is the specific heat capacity,  $w_t$  is the blood perfusion in a tissue.

Debye-Huckel model [43] for potential across the interfacial double layer: A metal surface in contact with an electrolyte typically acquires a charge of  $0.2\text{Cm}^{-2}$  because of the formation of the electrode-electrolyte interface. Additionally, an external signal is applied to the electrode deposits additional charge on the metal surface given by (S17)

$$\sigma_{dep} = C_{dl} \cdot V_{electrode} \quad (\text{S17})$$

where  $\sigma_{dep}$  is the charge density deposited in  $\text{Cm}^{-2}$ ,  $C_{dl}$  and  $V_{electrode}$  are as above. At peak amplitude of a 10V sinusoidal signal,  $\sigma_{dep}$  can be calculated to be  $0.023\text{Cm}^{-2}$  for the measured  $C_{dl}$  and  $A_{elec}$  bringing the total charge density  $\sigma_{total}$  to  $0.223\text{Cm}^{-2}$ . The potential  $V_{dl}$  across the double layer can then be calculated to be

$$V_{dl} = \kappa^{-1} \cdot \sigma_{total} / \epsilon_r \epsilon_0 \quad (\text{S18})$$

where  $\epsilon_r$  is the relative permittivity of the medium,  $\epsilon_0$  is the permittivity of free space ( $\text{Fm}^{-1}$ ) and  $\kappa^{-1}$  is the Debye length for the given solution.  $\kappa^{-1}$  depends on the ionic strength of the solution, which for a one-one electrolyte ( $\text{Na}^+$  and  $\text{Cl}^-$ , in our case) is equal to the concentration. The Debye length is calculated according to (S19)

$$\kappa^{-1} = \sqrt{\frac{\epsilon_r \epsilon_0 k_B T}{2 N_A e^2 I}} \quad (\text{S19})$$

$k_B$  is Boltzmann's constant,  $N_A$  is Avogadro's constant,  $e$  is the elementary charge,  $T$  is the temperature in K, and  $I$  is the ionic strength in  $\text{molm}^{-3}$ .  $\kappa^{-1}$  is found to be 0.828 nm, which is consistent with typical values found in literature ( $\sim 1\text{nm}$ ). In our case,  $V_{dl}$  is calculated to be 0.32V, with an RMS value of  $V_{cap} = 0.23V$ .