Epileptogenicity biomarkers and effective connectivity in stereo-EEG

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Disclosures

- VP, Chief Techological Officer, FHC Inc, Bowdoin, Maine, USA

Outline

- Signal analysis methods developed and used in Bucharest for analysis of SEEG recordings:
  - Epileptogenicity biomarkers / mapping
  - Functional connectivity
- Spontaneous activity
  - ~~Inter-ictal: spikes, HFO~~
  - Ictal: epileptogenicity indexes
- Responses to intracranial stimulation
  - Low frequency – SPES (f<0.1 Hz)
    - Biomarkers: HFO, Delayed Responses
    - Effective connectivity using CCEP – brain connectome
  - High frequency (f=50 Hz)
    - Functional connectivity during stimulation

- Clinical value of the signal analysis methods:
  - S56 Thu 9:40 AM, Ioana Mindruta
    - ADDED VALUE OF EEG SIGNAL ANALYSIS IN PRESURGICAL EVALUATION FOR DRUG-RESISTANT EPILEPSY
  - O154 Fri 14:15, Mihai Dragos Maliia
    - DEACTIVATION OF DEFAULT MODE NETWORK IN FOCAL EPILEPSY, INFERRED BY SINGLE PULSE ELECTRICAL STIMULATION
  - O157 Fri 14:45, Irina Popa
    - MAPPING THE FUNCTION AND CONNECTIVITY OF THE CINGULATE GYRUS USING STEREO-ENCEPHALOGRAPHY (SEEG)
  - P241, Fri 11:45, Anca Adriana Arbune
    - INSULA CONNECTIVITY DURING WAKEFULNESS AND SLEEP STUDIED THROUGH SINGLE PULSE ELECTRICAL STIMULATION DURING SEEG RECORDINGS

Instantaneous weighted power ratio

- Both ictal LVFA associated with flattening (Spanedda et al., Epilepsia 1997) and baseline shifts (Ikeda et al., Epilepsia 1996) are considered to be robust biomarkers of epileptogenicity (Perucca, Dubeau and Gotman, Brain 2014).
- We therefore combine LVFA (γ + HFO) and slow (<0.5Hz) activity in a weighted power ratio:

Pure LVFA + DC

$$IWPR = \frac{w \cdot (P_{\gamma} + P_{HFO}) + P_{Slow}}{w \cdot (P_{\gamma} + P_{HFO}) + P_{Slow} + (P_{\alpha} + P_{\beta})}, \qquad 0 \le IWPR \le 1$$

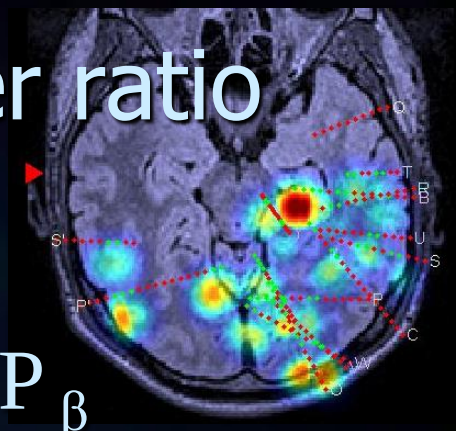
where w = weighting factor (typ. 10) for the DC shifts (DC shifts contain much larger energy than LVFA, obscuring LVFA)

- We calculate the instantaneous IWPR (IWPR) using Hilbert Transform
  - Returns "analytic signal" having modulus proportional to the signal envelope:

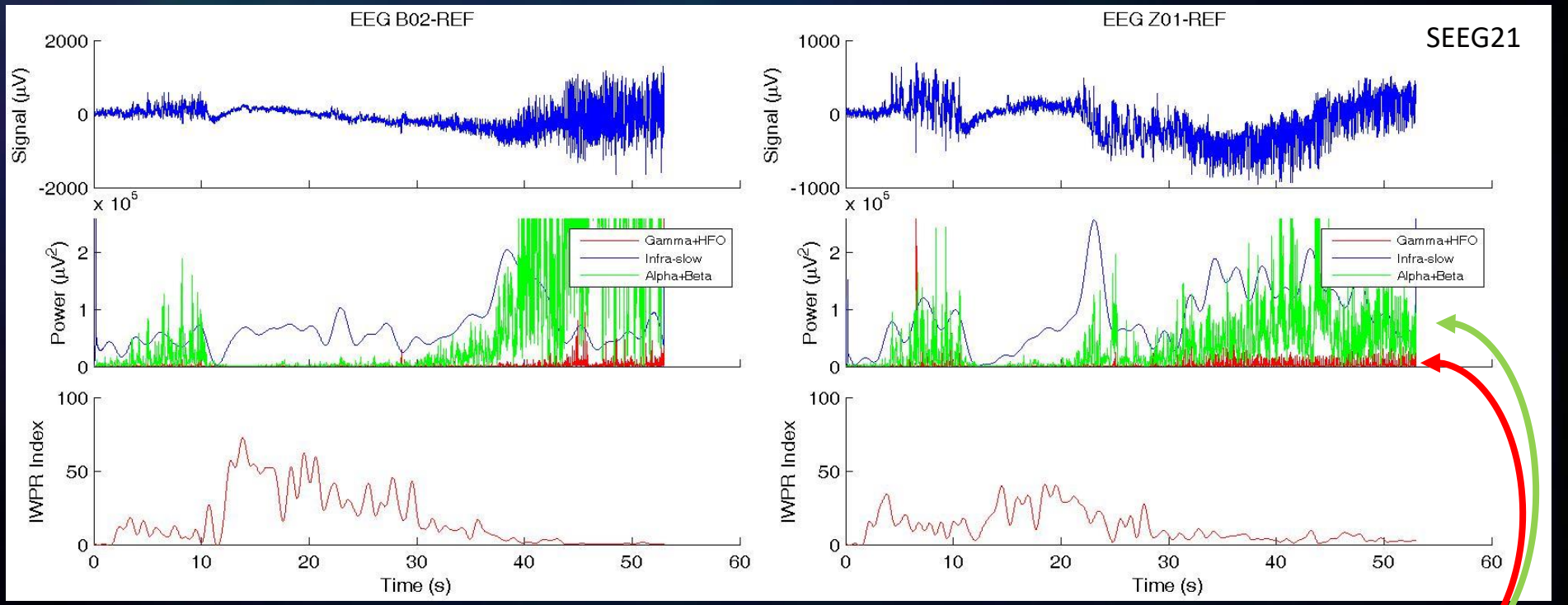
$$|x_a(t)| = \sqrt{x^2(t) + H^2(x)(t)}$$

- We apply HT to calculate instantaneous aEEG over several frequency bands of interest.
- We calculate an instantaneous signal power ratio (IWPR) for all contacts and perform a 3D topographic animated representation overlapped with patient's anatomy.

Instantaneous weighted power ratio (IWPR)

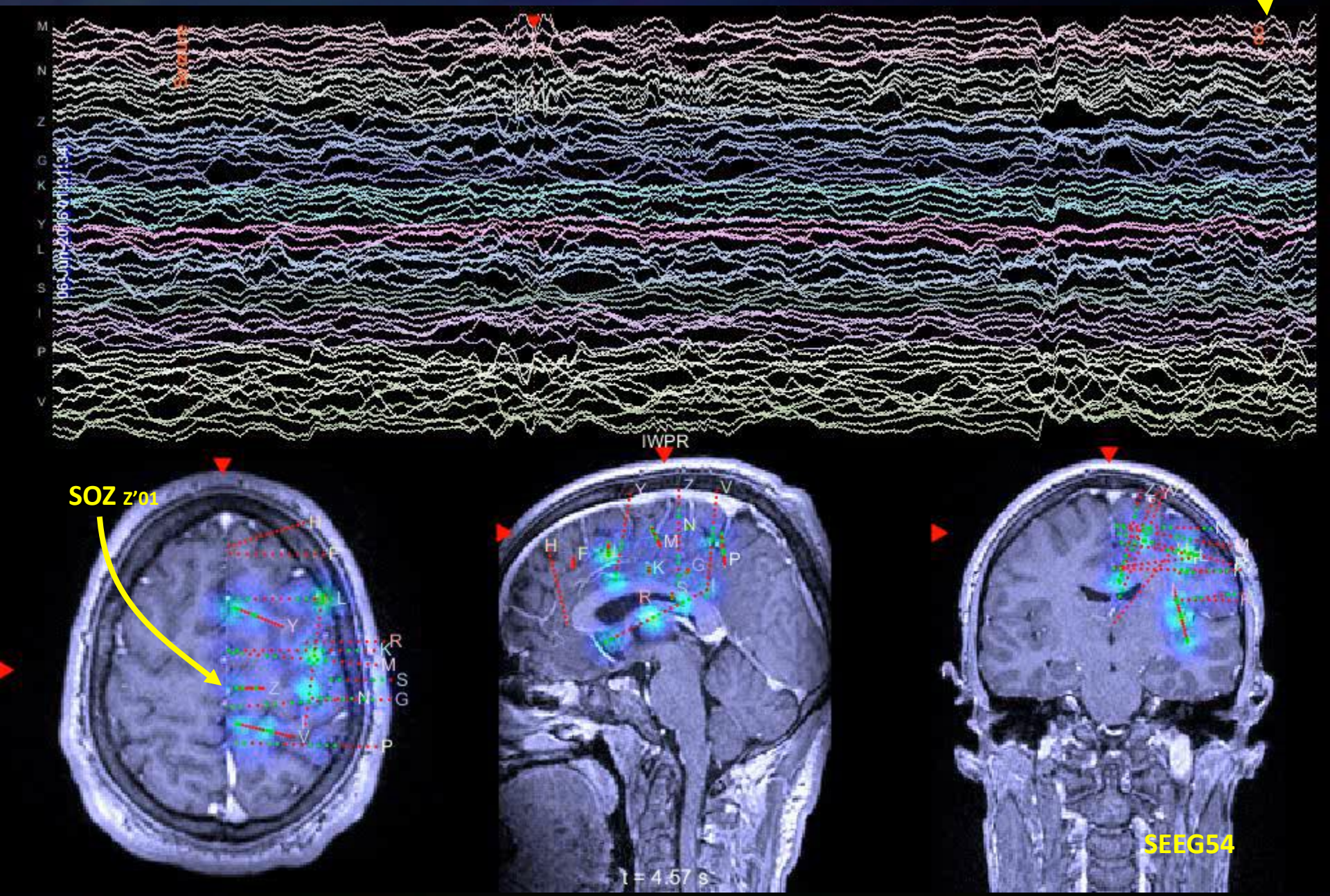


- $w \cdot (P_{\gamma} + P_{HFO}) + P_{Slow}$ **vs** $P_{\alpha} + P_{\beta}$



- P_{γ}, P_{HFO}, P_{slow} , P_{α}, P_{β} – power in respective freq. bands
- w – a weight of the high-frequency range vs baseline shift power, (w~10)

Topographic mapping of IWER



Epileptogenicity biomarkers: HFO and DR

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journal homepage: www.elsevier.com/locate/clinph

Co-occurrence of high-frequency oscillations and delayed responses evoked by intracranial electrical stimulation in stereo-EEG studies

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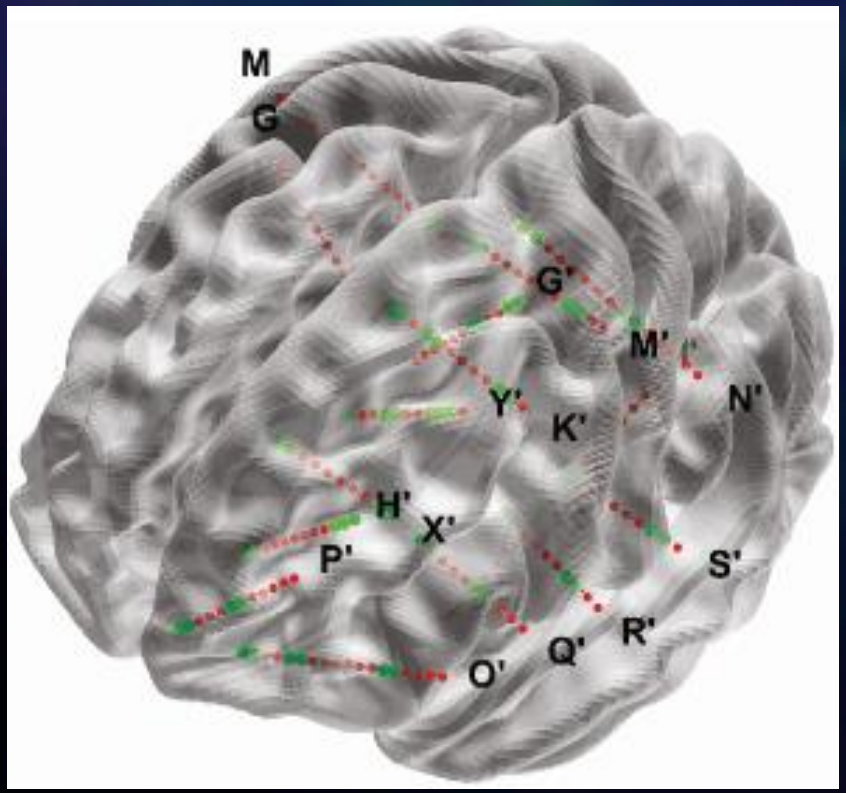
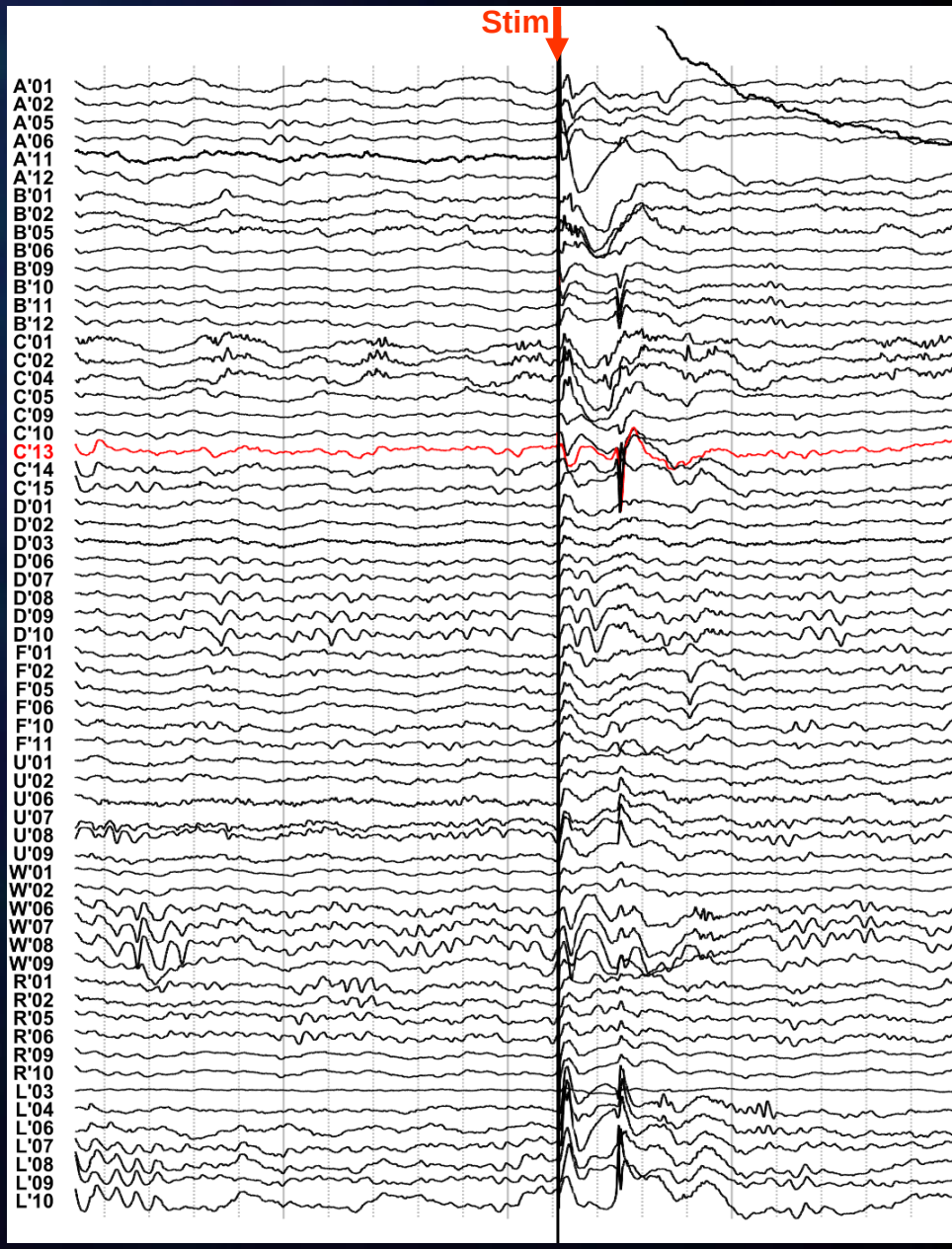
Epileptogenicity biomarkers

- HFO and DR evoked by inter-ictal single-pulse intracranial electrical stimulation in 16 patients
- Sensitivity, Specificity, Accuracy, Positive Prediction Value for identifying Seizure Onset Zone (SOZ)





Brain (2002), **125,** 1709–1718

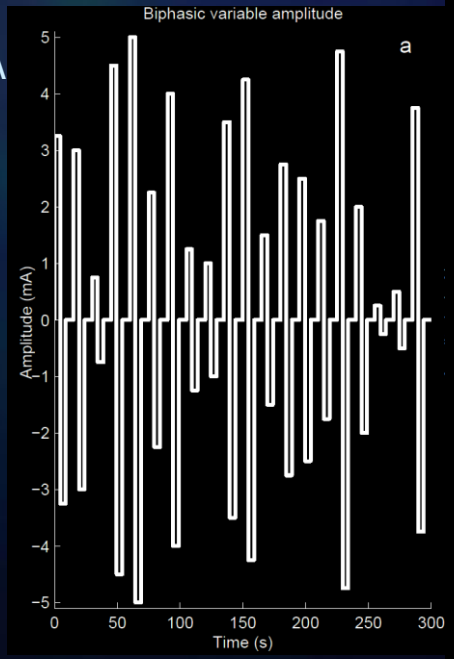
Responses to single pulse electrical stimulation identify epileptogenesis in the human brain *in vivo*

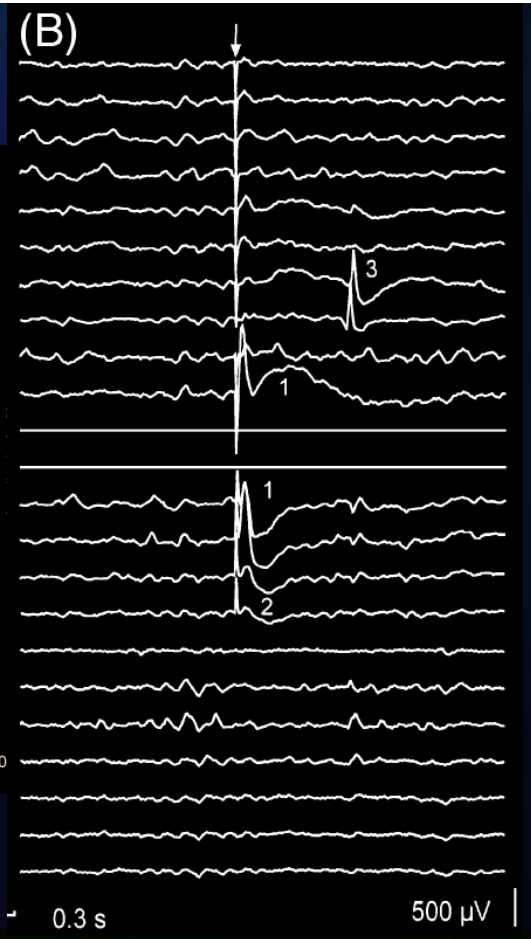
A. Valentín,[1] M. Anderson,[1] G. Alarcón,[1,2] J. J. García Seoane,[2] R. Selway,[1] C. D. Binnie[1] and C. E. Polkey[1]

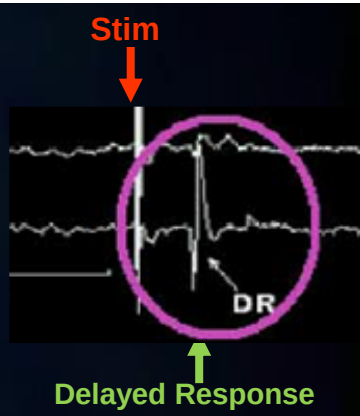
Current intensity I = 0.25-5 mA
Pulse width t = 3 ms
Interpulse interval IPI = 15 s

20 pulses with variable amplitude in pseudo-random sequence

Waveform and sequence programmed in Guideline4000 LP+(FHC Inc, Bowdoin, ME)



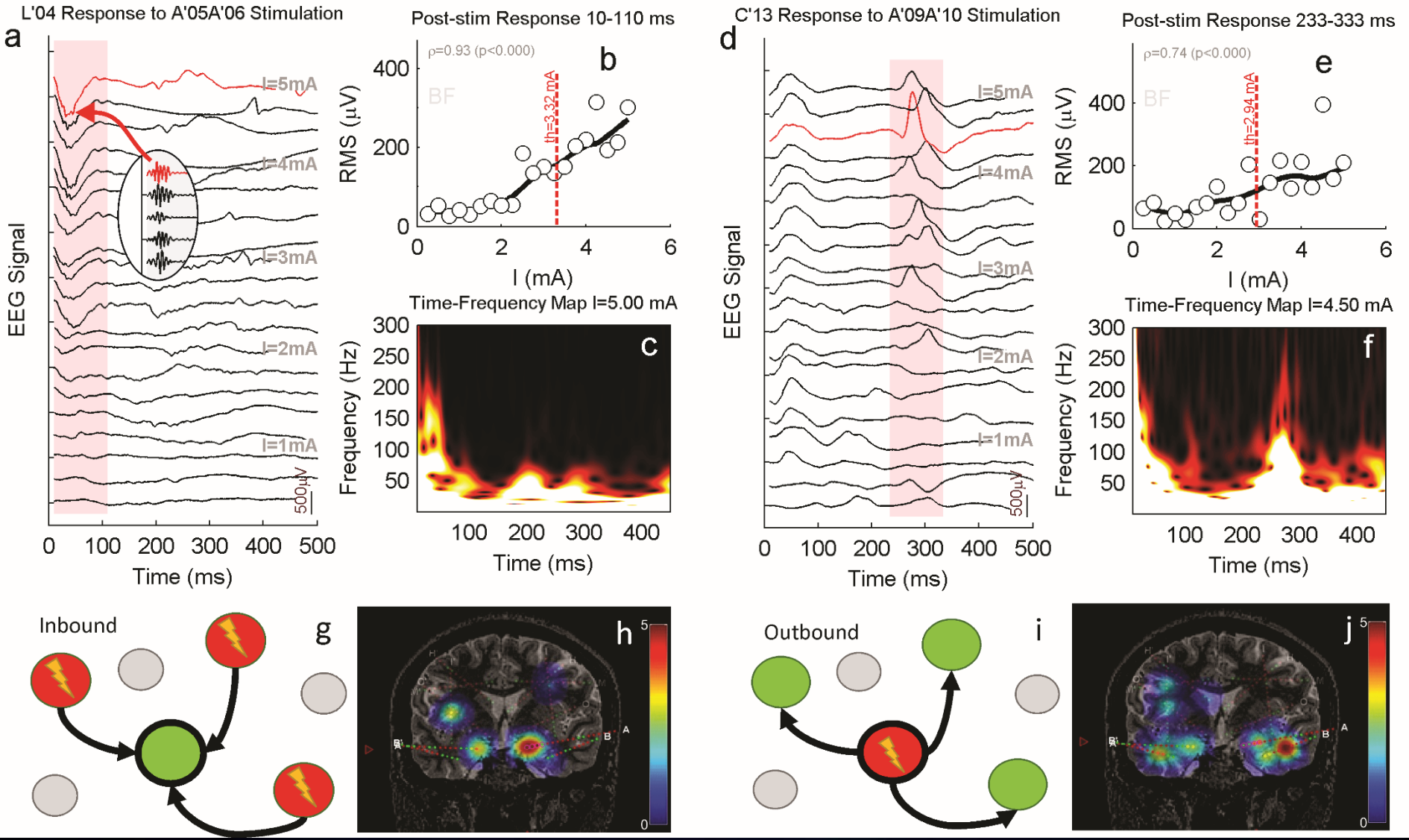




1 & 2:
Early Responses
< 100 ms

3: Delayed Responses > 100 ms

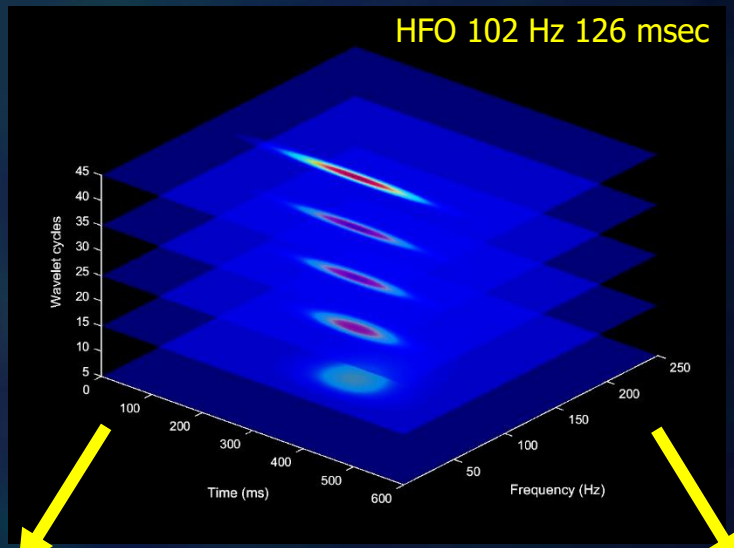
High-Frequency Oscillations and Delayed Responses evoked by SPES

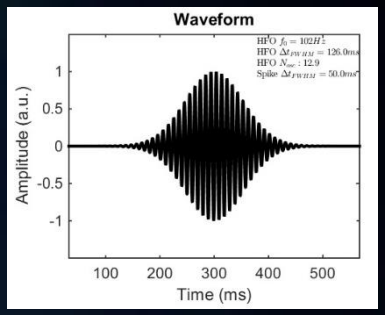


Donos C, Mîndruţă I, Malîia MD, Raşină A, Ciurea J, Barborica A (2016). Clin Neurophysiol 2017, doi:10.1016/j.clinph.2016.11.028.

Time-frequency analysis using signal-adapted wavelets

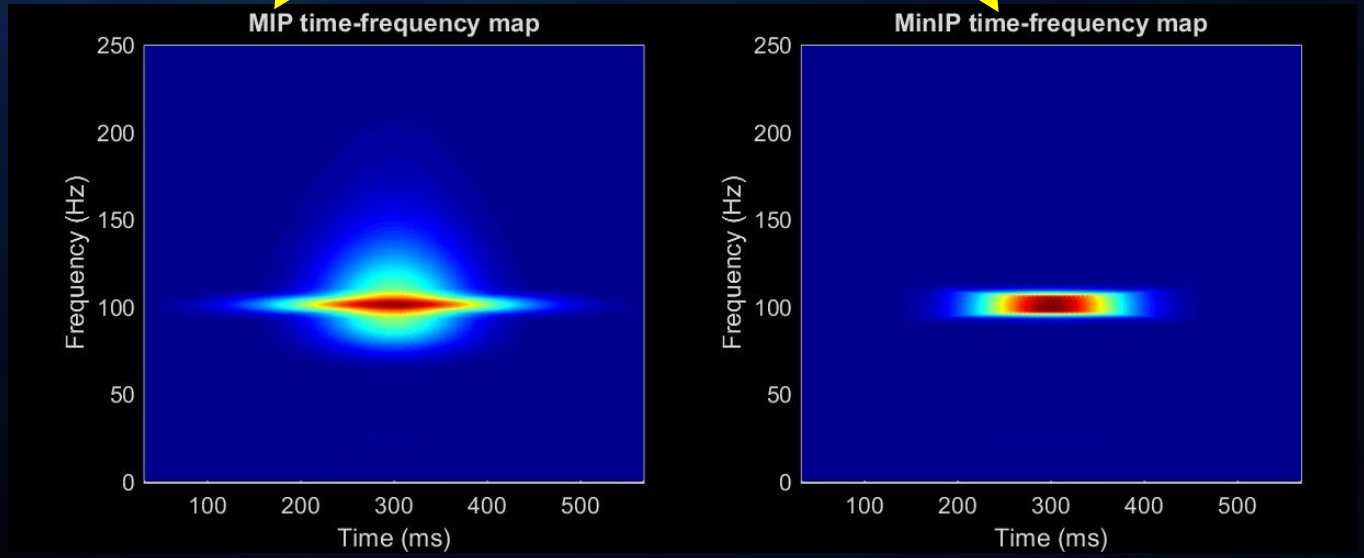
Combine information with good time localization and frequency resolution, obtained by varying the Q-factor of the mother wavelet





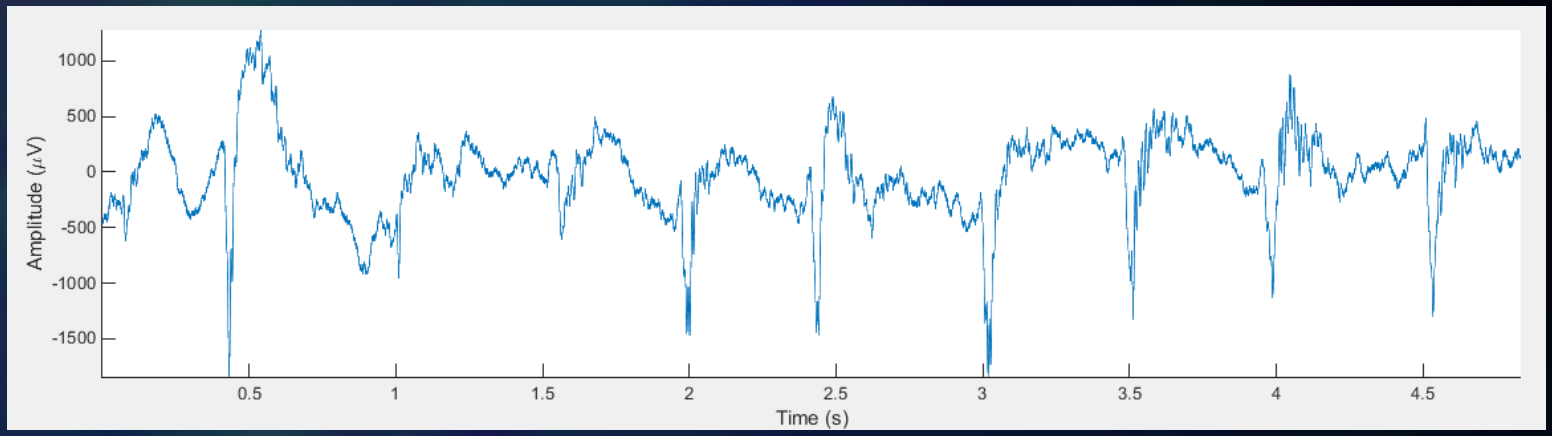
Maximum intensity projection - MIP

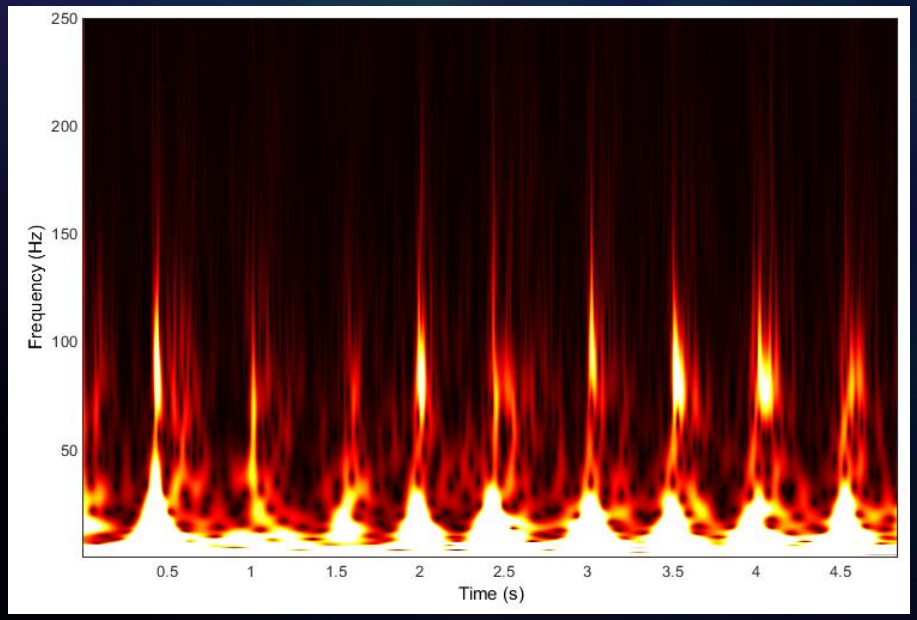
Minimum intensity projection - MinIP



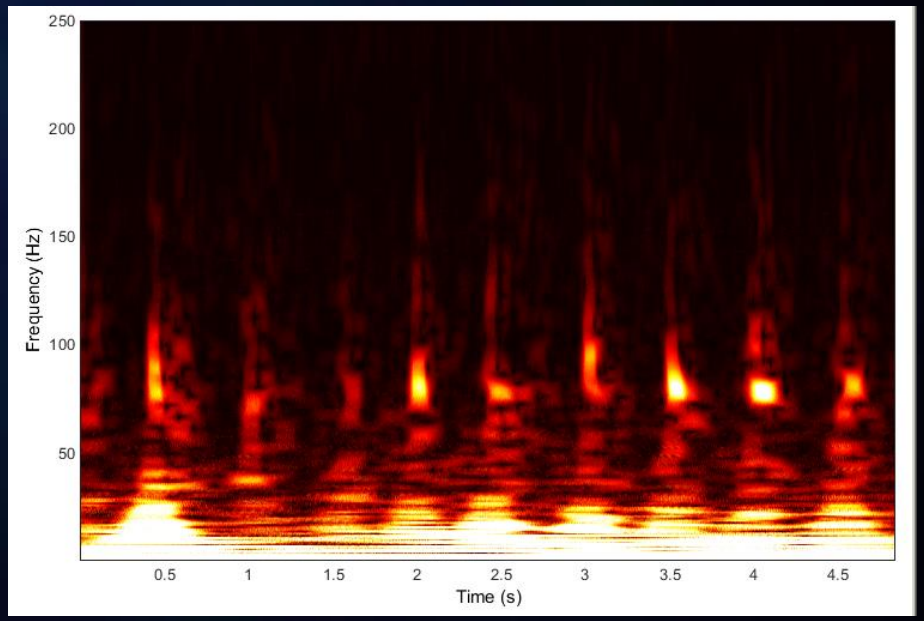
Matlab File Exchange: **57348**

- Repetitive inter-ictal spikes + HFO on SEEG macrocontacts





Morlet



Multi-Q MinIP

Patient Population (n=16)

Patient	Sex	Age	Lateralization	Number of Electrodes	SOZ	Resection	Pathology	Surgical Outcome	Follow up (months)
1	F	40	L	11	Prefrontal Lateral (SFG, MFG)	Lesionectomy	Type II B cortical dysplasia	Engel I A	23
2	F	35	R	12	Amygdala	Temporal lobectomy	Type III cortical dysplasia (Temporal Sclerosis + II A)	Engel IA	10
3	F	24	R	15	Precentral Gyrus (MFG, IFG), Rolandic Operculum	Lesionectomy	Type II A cortical dysplasia	Engel III A	21
4	M	24	R	14	Occipital, Temporal Basal	Occipital lobectomy, Temporal basal corticectectomy	Type I cortical dysplasia	Engel III B	23
5	F	25	R	10	Temporal Pole	Temporal lobectomy	Type I cortical dysplasia	Engel I D	25
6	F	46	R	9	Superior Temporal Gyrus	Temporal lateral corticectectomy	Type II B cortical dysplasia	Engel IV C	20
7	M	33	L	17	Prefrontal-Premotor Mesial	Frontal mesial corticectectomy	Type II A cortical dysplasia	Engel I A	17
8	F	11	R	9	Prefrontal-Premotor Mesio-Lateral (SFG)	Frontal mesio-lateral corticectectomy	Type II A cortical dysplasia	Engel I A	21
9	M	28	R	17	Hippocampus	Temporal lobectomy	Type I cortical dysplasia	Engel I A	19
10	M	39	L	16	Lingual Gyrus	Occipital basal corticectectomy	Polimycrogyria	Engel I A	34
11	M	47	L	11	Middle Temporal Gyrus	Lesionectomy	DNET	Engel II B	28
12	F	37	L	13	Amygdala, Enthorinal, Hippocampus, Temporal Pole	Temporal lobectomy	Hippocampal sclerosis	Engel I A	15
13	F	36	R	15	Parieto-Temporal Operculum, Posterior Insula	Lesionectomy	Type II B cortical dysplasia	Engel I A	15
14	F	42	R	14	Amygdala, Temporal Pole	Temporal lobectomy	Type I cortical dysplasia	Engel I A	15
15	M	30	R	15	Prefrontal Lateral (IFG)	RFTC	Not available (coagulated)	Engel I A	6
16	M	42	L	14	Amygdala, Enthorinal, Hippocampus	Partial temporal lobectomy	Type II A cortical dysplasia	Engel I A	9

A total of 212 electrodes (mean 13.3) electrodes containing 2612 (mean 163.3) contacts were implanted; 64 channels per patient have been recorded (total 1024).

Biomarker Metrics

- By Number of Contacts

$$Sens_C = \frac{NC_{SOZ}^{POS}}{NC_{SOZ}}$$

$$Spec_C = \frac{NC_{NSOZ}^{NEG}}{NC_{NSOZ}}$$

$$Acc_C = \frac{NC_{SOZ}^{POS} + NC_{NSOZ}^{NEG}}{NC}$$

$$PPV_C = \frac{NC_{SOZ}^{POS}}{NC_{SOZ}^{POS} + NC_{NSOZ}^{POS}}$$

- By Number of responses

$$POS_i = NR_i / \max(NR_i) \qquad NEG_i = 1 - NR_i / \max(NR_i)$$

$$TP = \frac{1}{\max(NR_i)} \sum_{i=1}^{NC_{SOZ}} NR_i^{SOZ} \qquad FP = \frac{1}{\max(NR_i)} \sum_{i=1}^{NC_{NSOZ}} NR_i^{NSOZ}$$

$$FN = \sum_{i=1}^{NC_{SOZ}} \left(1 - \frac{NR_i^{SOZ}}{\max(NR_i)}\right) \qquad TN = \sum_{i=1}^{NC_{NSOZ}} \left(1 - \frac{NR_i^{NSOZ}}{\max(NR_i)}\right)$$

$$Sens_R = \frac{TP}{TP + FN} = \frac{1}{NC_{NSOZ}} \sum_{i=1}^{NC_{SOZ}} \left(\frac{NR_i^{SOZ}}{\max(NR_i)}\right)$$

$$Spec_R = \frac{TN}{FP + TN} = \frac{1}{NC_{SOZ}} \sum_{i=1}^{NC_{NSOZ}} \left(1 - \frac{NR_i^{NSOZ}}{\max(NR_i)}\right)$$

$$Acc_R = \frac{TP + TN}{TP + TN + FP + FN} = \frac{1}{NC}\left(\sum_{i=1}^{NC_{SOZ}} \left(\frac{NR_i^{SOZ}}{\max(NR_i)}\right) + \sum_{i=1}^{NC_{NSOZ}} \left(1 - \frac{NR_i^{NSOZ}}{\max(NR_i)}\right)\right)$$

$$PPV_R = \frac{TP}{TP + FP} = \frac{\sum_{i=1}^{NC_{SOZ}} NR_i^{SOZ}}{\sum_{i=1}^{NC} NR_i}$$

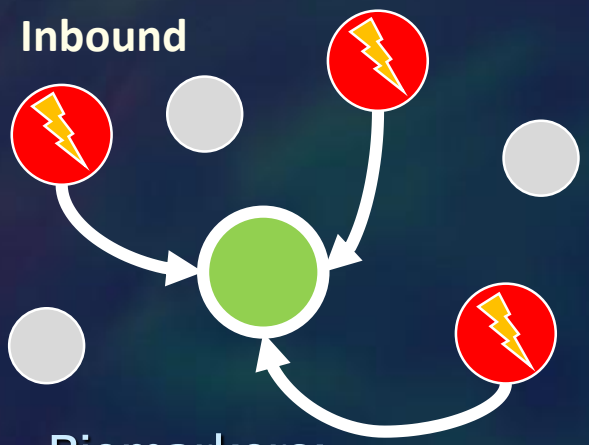
$$NPV_R = \frac{TN}{TN + FN} = \frac{\sum_{i=1}^{NC_{NSOZ}} \left(1 - \frac{NR_i^{NSOZ}}{\max(NR_i)}\right)}{\sum_{i=1}^{NC} \left(1 - \frac{NR_i}{\max(NR_i)}\right)}$$

- Similarity (Jaccard):

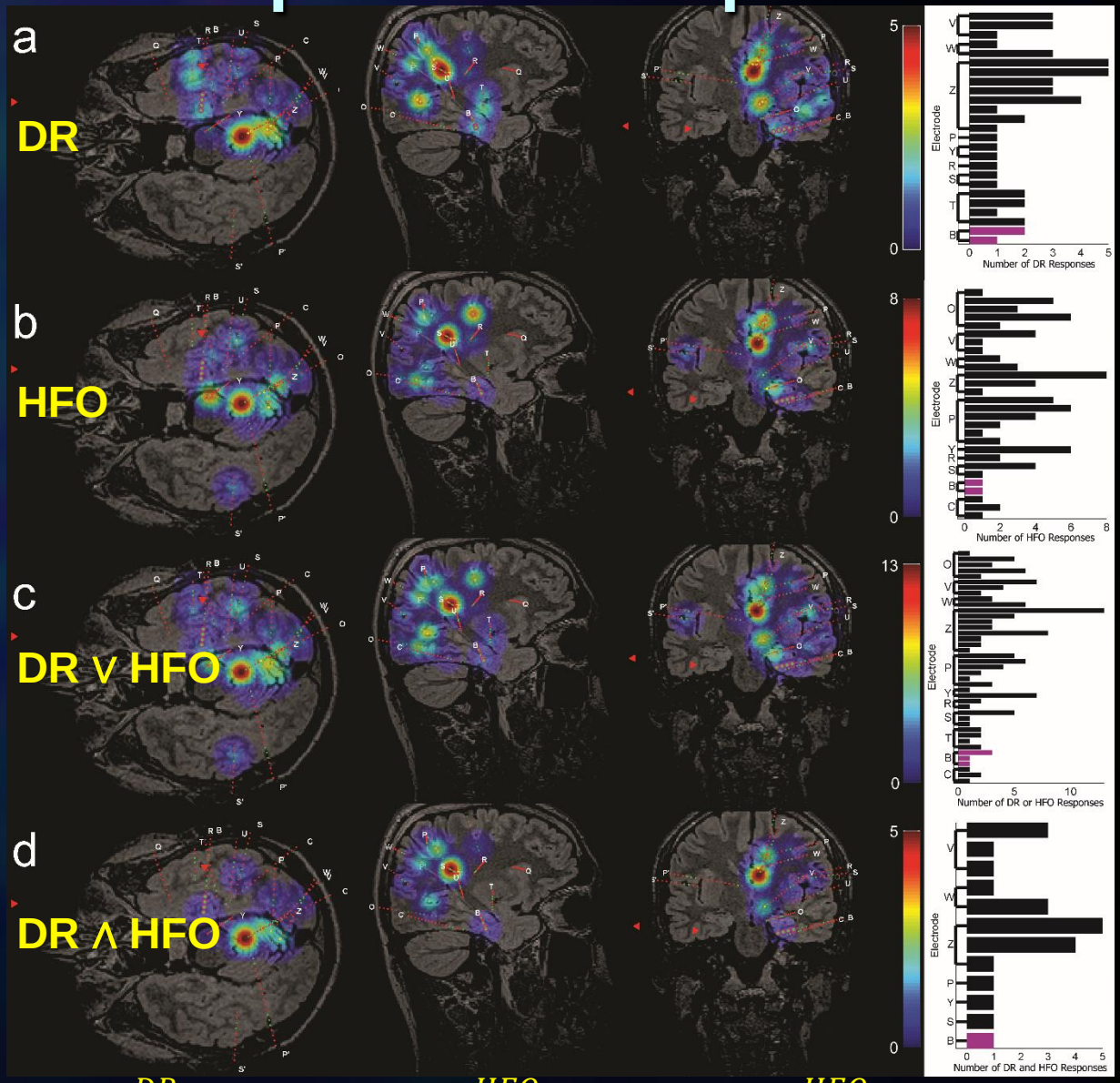
$$J(DR, HFO) = \frac{|DR \cap HFO|}{|DR \cup HFO|} = \frac{NC_{DR \wedge HFO}}{NC_{DR \vee HFO}}$$

$$J(DR, HFO) = \frac{\sum_{i=1}^{NC} \min(NR_i^{DR}, NR_i^{HFO})}{\sum_{i=1}^{NC} \max(NR_i^{DR}, NR_i^{HFO})}$$

Inbound Response Maps

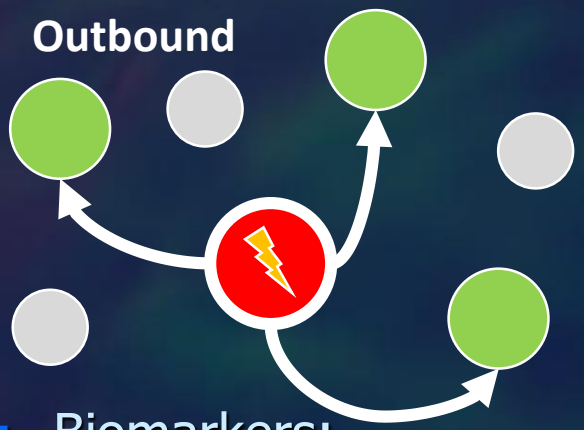


- Biomarkers:
  - DR
  - HFO
- Combinations “or”, “and”:
  - DR ∨ HFO
  - DR ∧ HFO
- Maps:
  - Number of responses DR, HFO, DR∧HFO, DR∨HFO



Patient #9: $Sens_C^{DR} = 50\%$, $Spec_C^{DR} = 61.7\%$, $Sens_C^{HFO} = 50\%$, $Spec_C^{HFO} = 56.7\%$, $Sens_C^{DR \vee HFO} = 75\%$, $Spec_C^{DR \vee HFO} = 36.7\%$, $Sens_C^{DR \wedge HFO} = 25\%$, $Spec_C^{DR \wedge HFO} = 81.7\%$,

Outbound Response Maps



- Biomarkers:
  - DR
  - HFO
- Combinations "or", "and":
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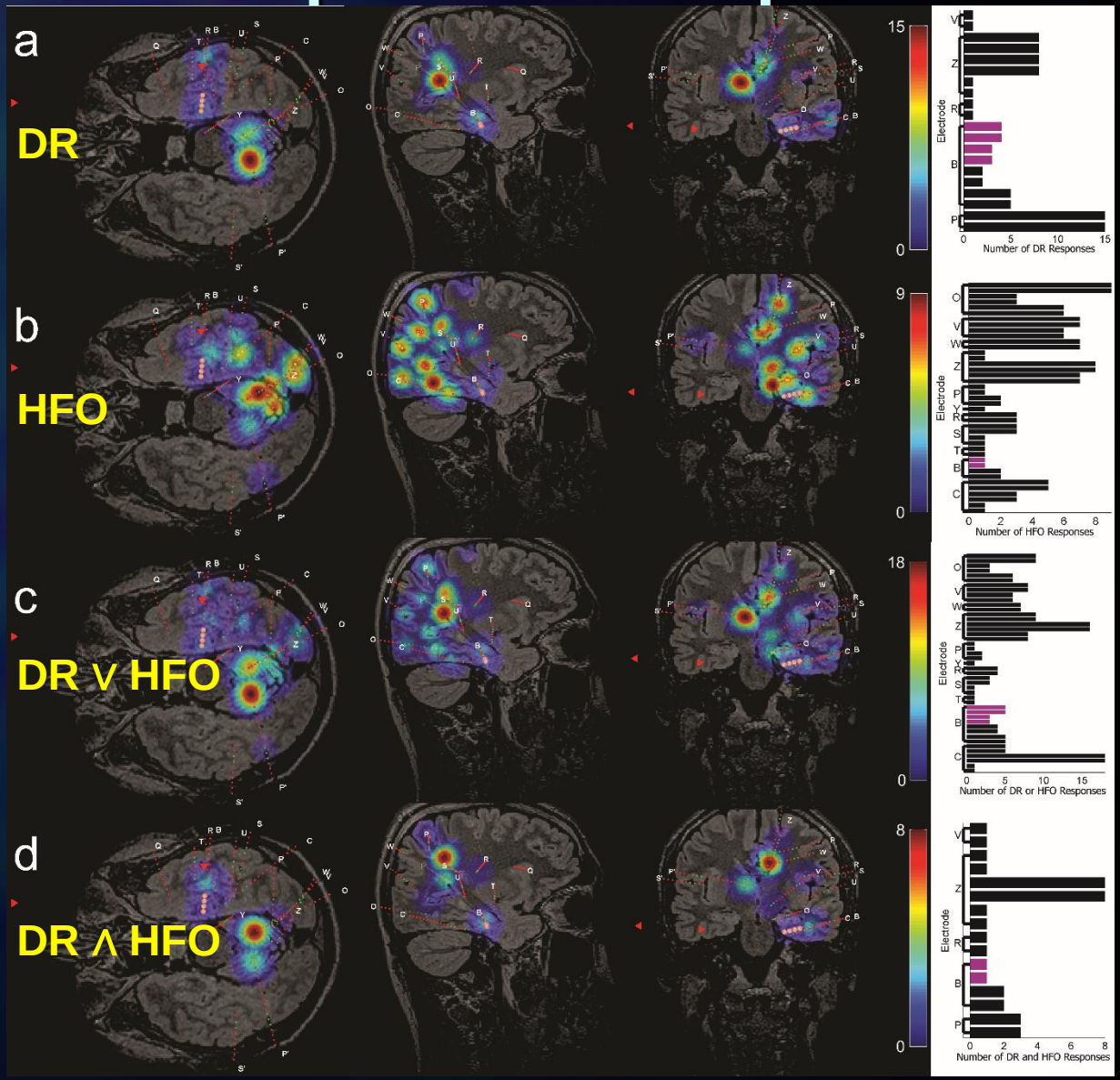
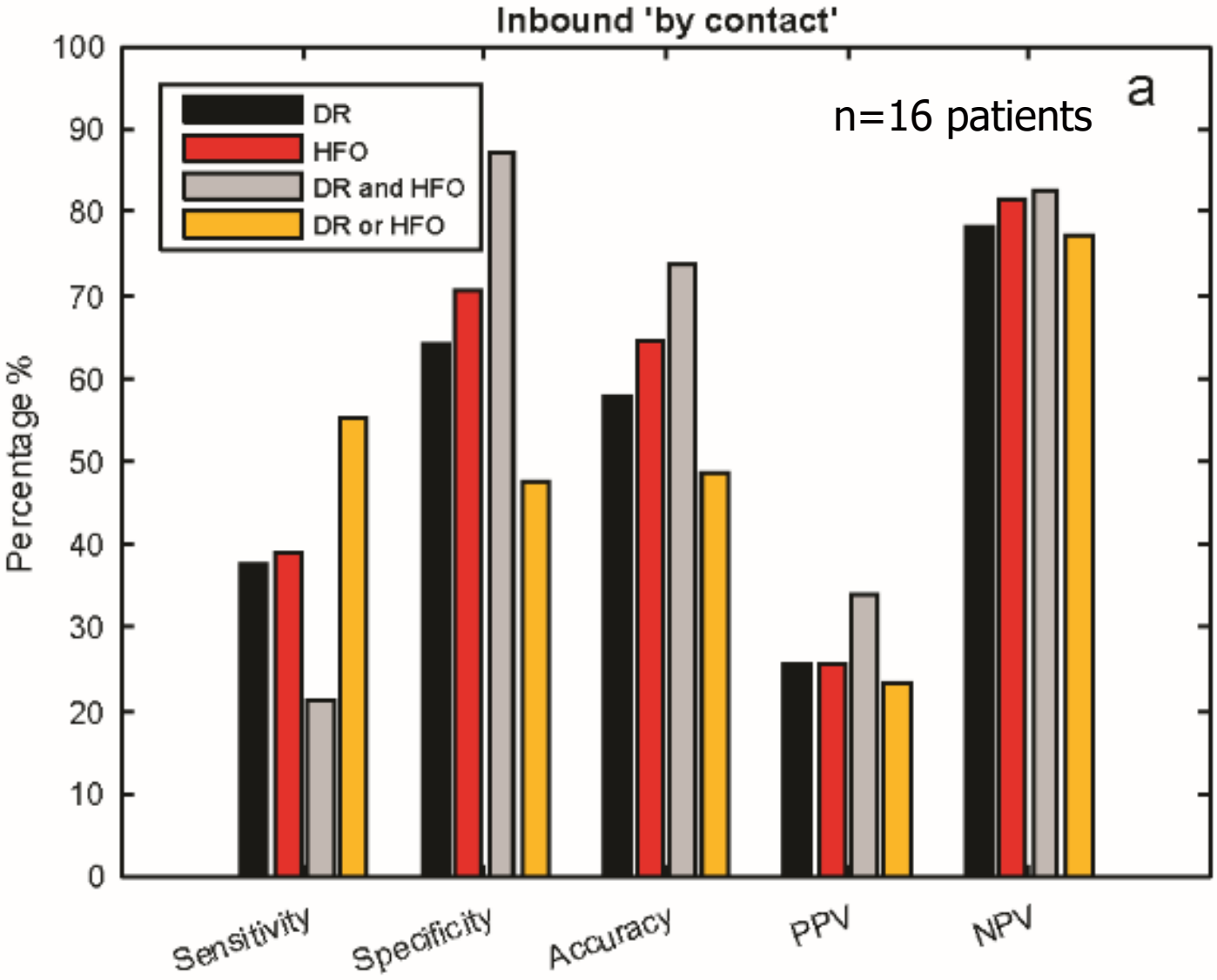
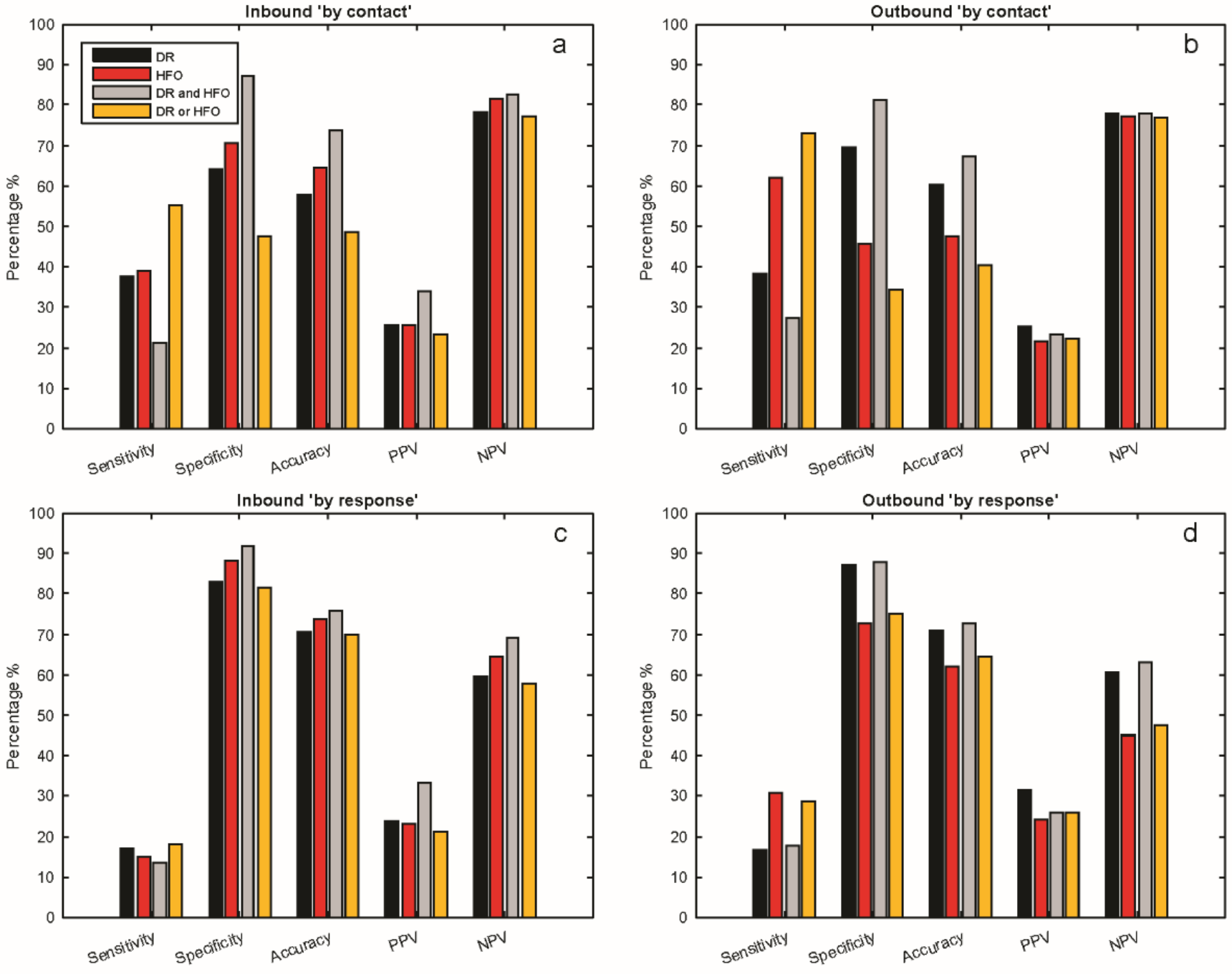
- Maps:
  - Number of responses DR, HFO, DR∧HFO, DR∨HFO



Patient #9: $Sens_C^{DR} = 100\%$, $Spec_C^{DR} = 70.9\%$, $Sens_C^{HFO} = 50\%$, $Spec_C^{HFO} = 29.1\%$, $Sens_C^{DR \vee HFO} = 100\%$, $Spec_C^{DR \vee HFO} 25.5\%$, $Sens_C^{DR \wedge HFO} = 50\%$, $Spec_C^{DR \wedge HFO} = 74.5\%$,

Biomarker Metrics




Inbound 'by contact'
a
DR
HFO
DR and HFO
DR or HFO
Percentage %
Sensitivity
Specificity
Accuracy
PPV
NPV
Outbound 'by contact'
b
Inbound 'by response'
c
Outbound 'by response'
d

Conclusions (epileptogenicity biomarkers)

- Topographic representation of ER/DR/HFO is a valuable aid for the epileptologist
- Analyzing biomarker metrics of SOZ localization shows no clear winner between DRs and HFOs, taken separately
  - HFO – slightly higher sensitivity and specificity for inbound "by contact"
  - DR - higher specificity for outbound "by contact"
  - Sensitivity of biomarkers was larger "by contact" than "by response"
  - Combinations of responses:
    - "and" – improves specificity and accuracy, but degrades sensitivity
    - "or" – improves sensitivity
    - PPV and NPV are little affected
  - Jaccard similarity between responses: 25% (inbound), 29% (outbound) – chances for pathological DR and HFO sharing same generation mechanism are small

Outline

- Signal analysis methods developed and used in Bucharest for analysis of SEEG recordings:
  - Epileptogenicity biomarkers / mapping
  - Functional connectivity
- Spontaneous activity
  - Ictal: epileptogenicity indexes
- Responses to intracranial stimulation
  - Low frequency – SPES ($f<0.1$ Hz)
    - Biomarkers: HFO, Delayed Responses
    - Effective connectivity using CCEP – brain connectome
  - High frequency ($f=50$ Hz)
    - Functional connectivity during stimulation

Human Connectomics

- Effective connectivity – causal interactions between different brain regions: "the influence one neural system exerts over another" (Friston, 1994).
- Probed using intracranial electrical stimulation

NeuroImage 132 (2016) 344–358

Contents lists available at ScienceDirect

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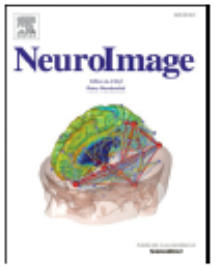

A connectomics approach combining structural and effective connectivity assessed by intracranial electrical stimulation

Cristian Donos [a], Mihai Dragoş Mălîia [b], Ioana Mîndruţă [b,c], Irina Popa [b], Mirela Ene [a], Bogdan Bălănescu [a,d], Ana Ciurea [a,d,e], Andrei Barborica [a,f,*]

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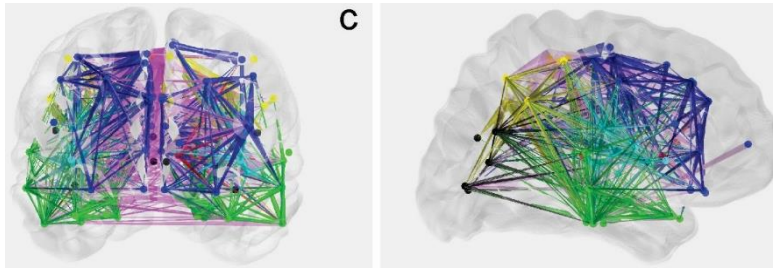
[c] Neurology Department, Carol Davila University of Medicine and Pharmacy, Bucharest, Romania
[d] Neurosurgery Department, Bagdasar-Arseni Emergency Hospital, Bucharest, Romania
[e] Neurology and Neurovascular Diseases National Institute, Bucharest, Romania
[f] FHC Inc, Bowdoin ME, USA

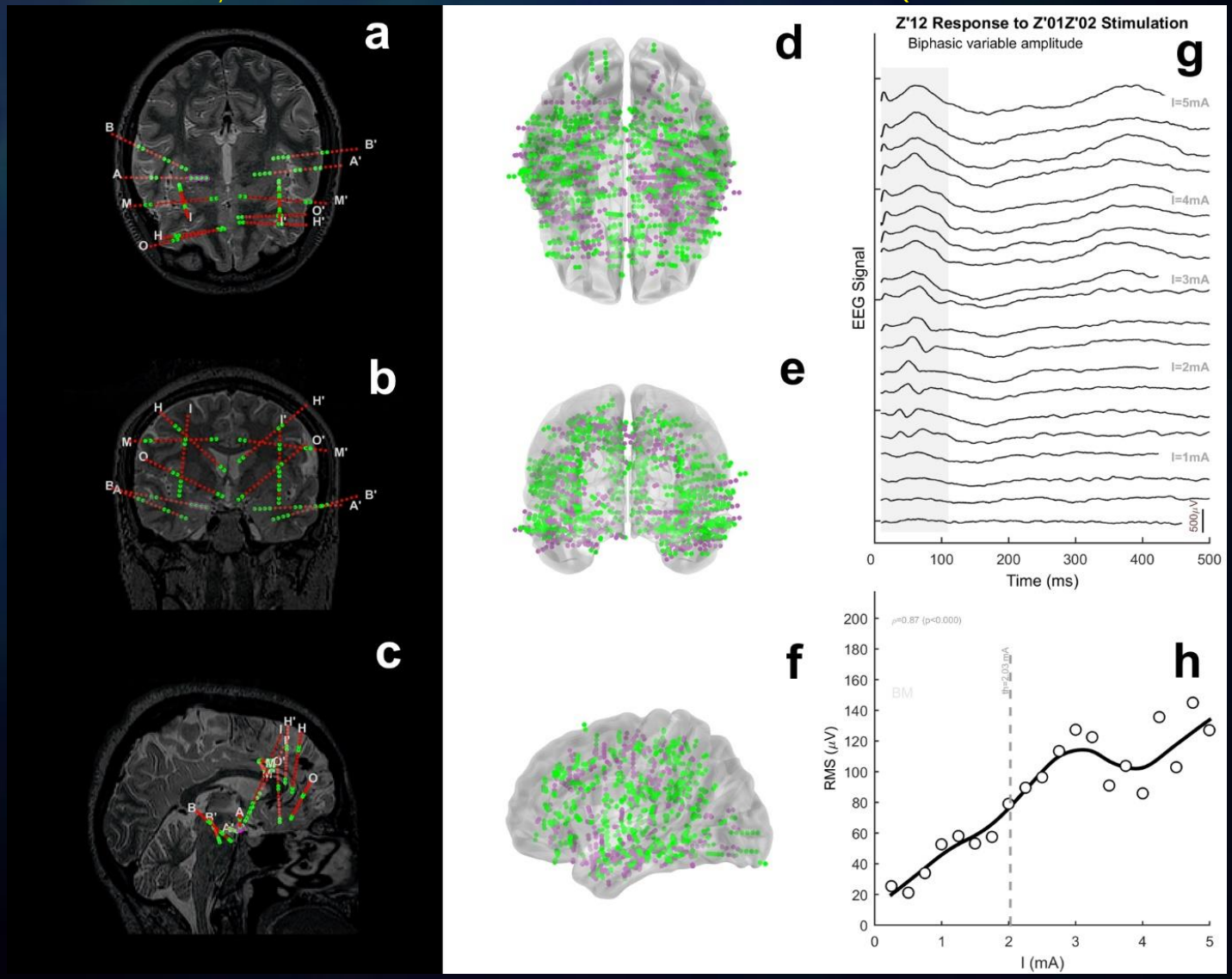


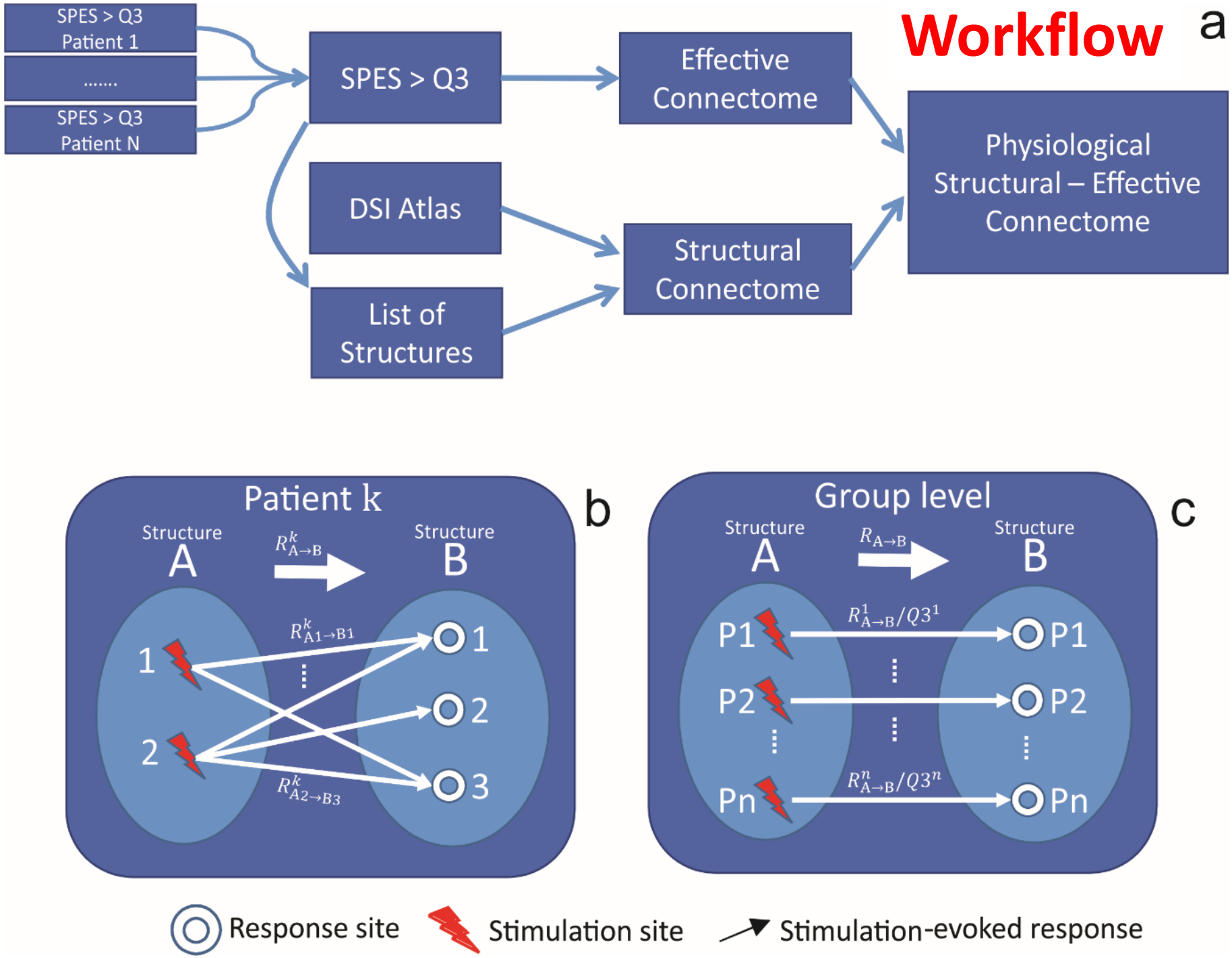
Spatial Sampling of the Brain

Single Patient (P5):
12 electrodes, 160 contacts

All 24 Patients:
308 electrodes, 1481 contacts

Responses to SPES: **ER**
(RMS over100 ms window)




Workflow
a
SPES > Q3 Patient 1
.....
SPES > Q3 Patient N
SPES > Q3
Effective Connectome
DSI Atlas
List of Structures
Structural Connectome
Physiological Structural – Effective Connectome
Patient k
b
Structure A
Structure B
$R^k_{A\to B}$
$R^k_{A1\to B1}$
$R^k_{A2\to B3}$
1
2
1
2
3
Group level
c
Structure A
Structure B
$R_{A\to B}$
$R^1_{A\to B}/Q3^1$
$R^n_{A\to B}/Q3^n$
P1
P2
Pn
P1
P2
Pn
Response site
Stimulation site
Stimulation-evoked response

Calculating Connectivity

- Patient-level effective connectivity $R^k_{A\to B}$ between *A* and *B* based on early responses to SPES, in patient *k*:

$$R^k_{A\to B} = \frac{\sum_{i=1}^{N^k_A}\sum_{j=1}^{N^k_B} R^k_{Ai\to Bj}}{N^k_{R_{AB}}}$$

- Group-level effective connectivity $R_{A\to B}$ obtained by averaging patient-level connectivity, normalized with the third quartile (*Q3*) of the responses:

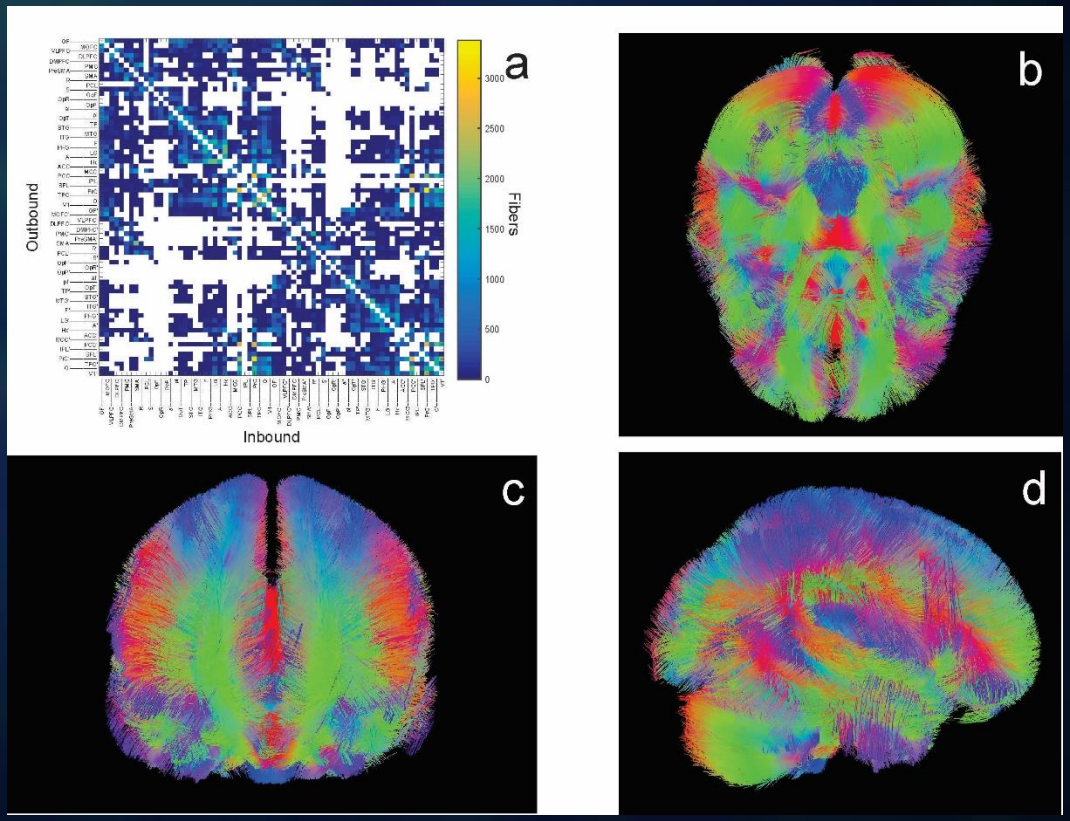
$$R_{A\to B} = \frac{\sum_{k=1}^{N}\frac{R^k_{AB}}{Q3^k}}{N}$$

- Directionality factor:

$$DF_{A\leftrightarrow B} = \left|\frac{R_{A\to B} - R_{B\to A}}{R_{A\to B} + R_{B\to A}}\right|$$

Calculating Connectivity

- Effective connectivity was mapped on 97167 fibers connecting each structure, based on the CMU-60 atlas (Yeh and Tseng, 2011):



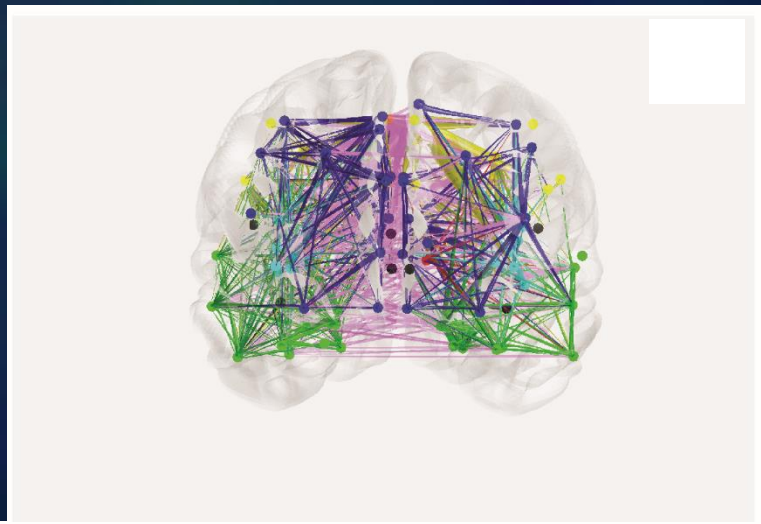
- Effective number of fibres:

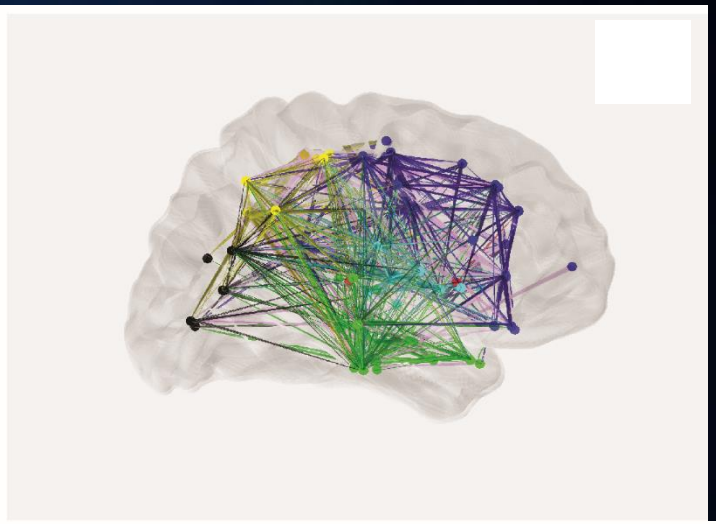
$$EF_{A\to B} = \frac{R_{A\to B}}{R_{A\to B} + R_{B\to A}} \cdot F_{AB}$$

Yeh F-C, Tseng W-YI (2011). NTU-90: a high angular resolution brain atlas constructed by q-space diffeomorphic reconstruction. Neuroimage 58(1):91-99.

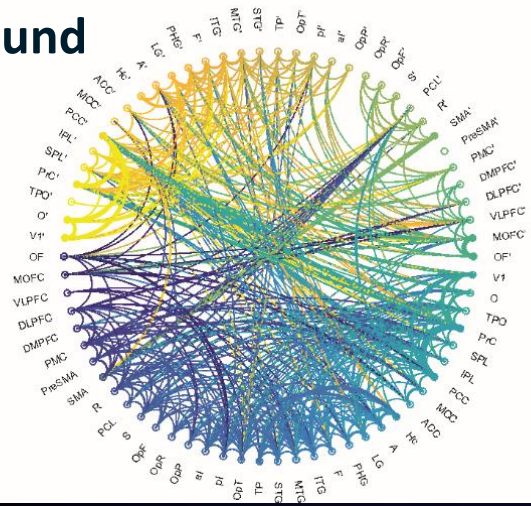
Physiological Connectome

Obtained by including only responses in non-pathological structures, averaged across patients (n=24)

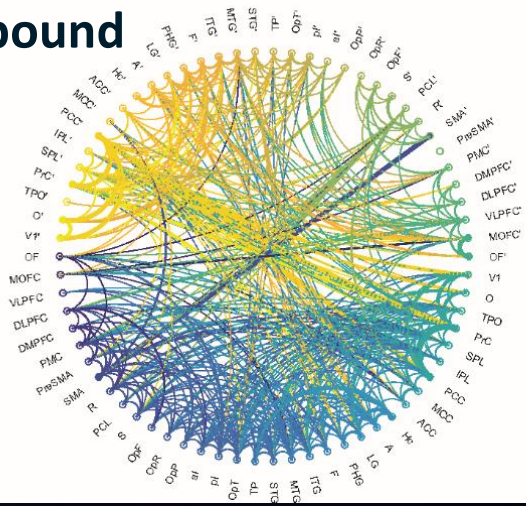




Inbound



Outbound

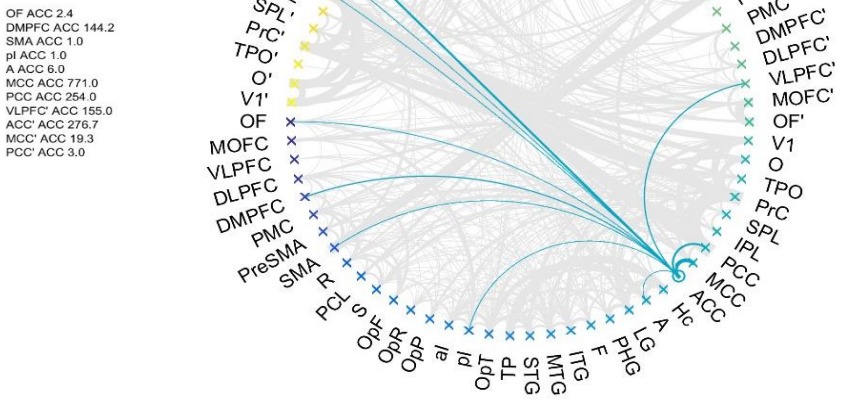


After Donos, Maliia, Mindruta, Popa, Ene, Balanescu, Ciurea, Barborica, *Neuroimage* 2016

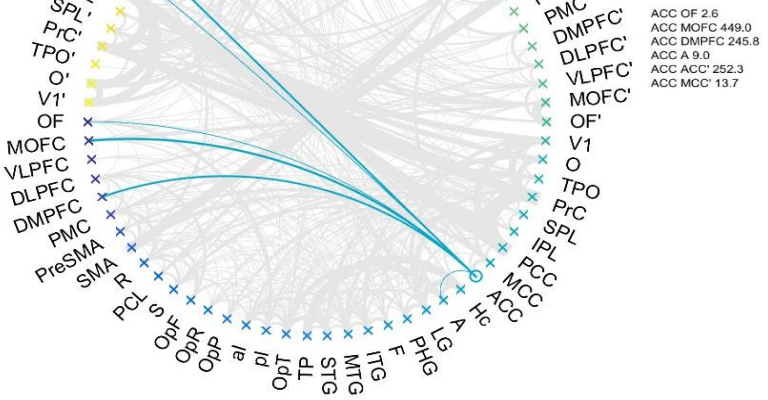
PSEC - Single Structure

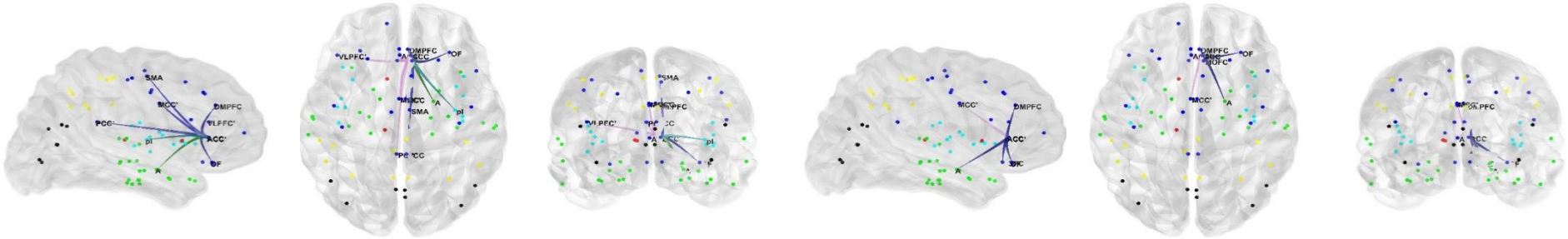
Right Anterior Cingulate – ACC Inbound/Outbound

Inbound



Outbound

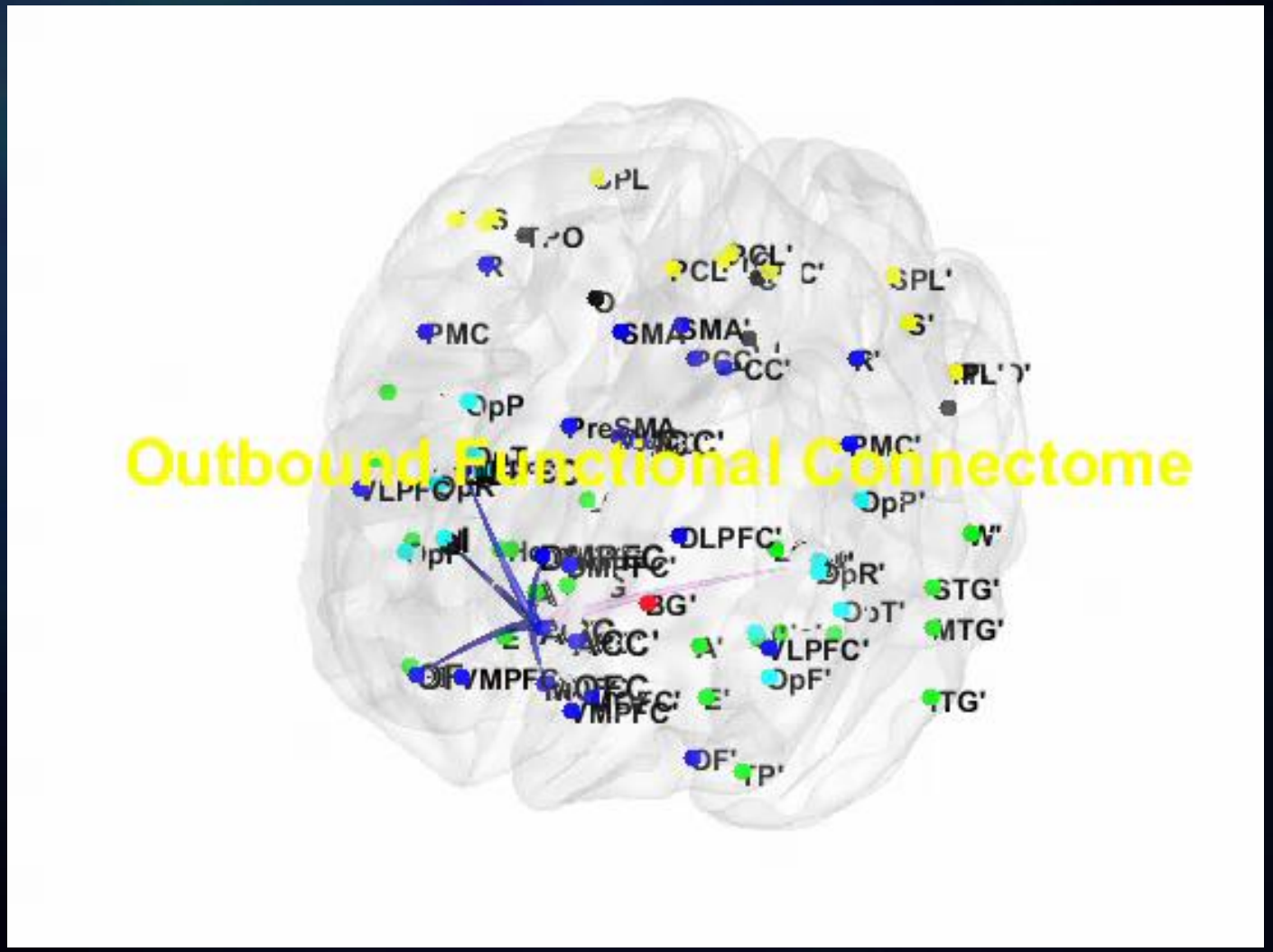




Functional Connectome
Single Structure

- Right Anterior Cingulate - ACC, 32 patients

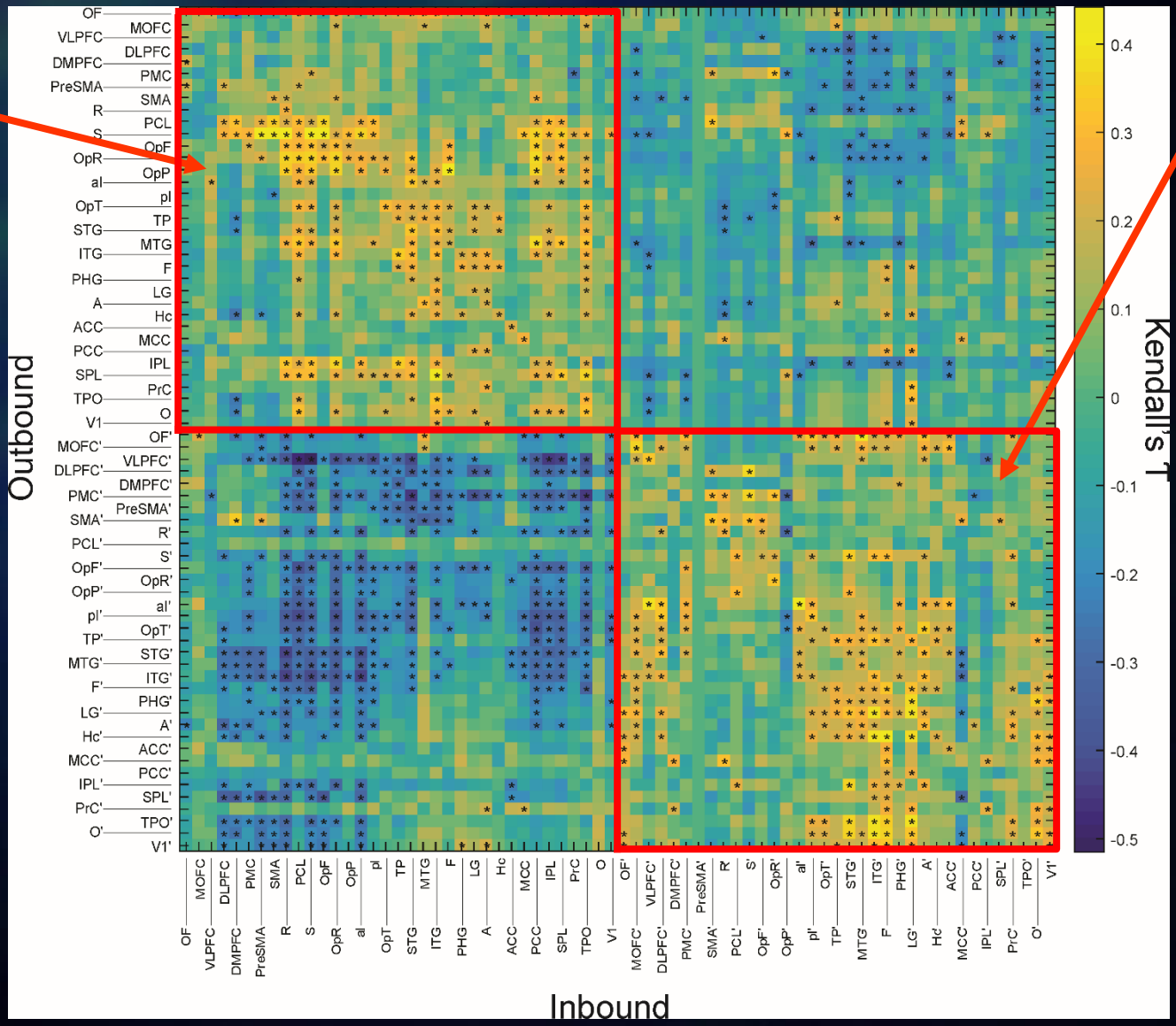
See Irina Popa O157 Thu 13:45



Correlation matrix between structural and effective connectome

Left Hemisphere

Right Hemisphere



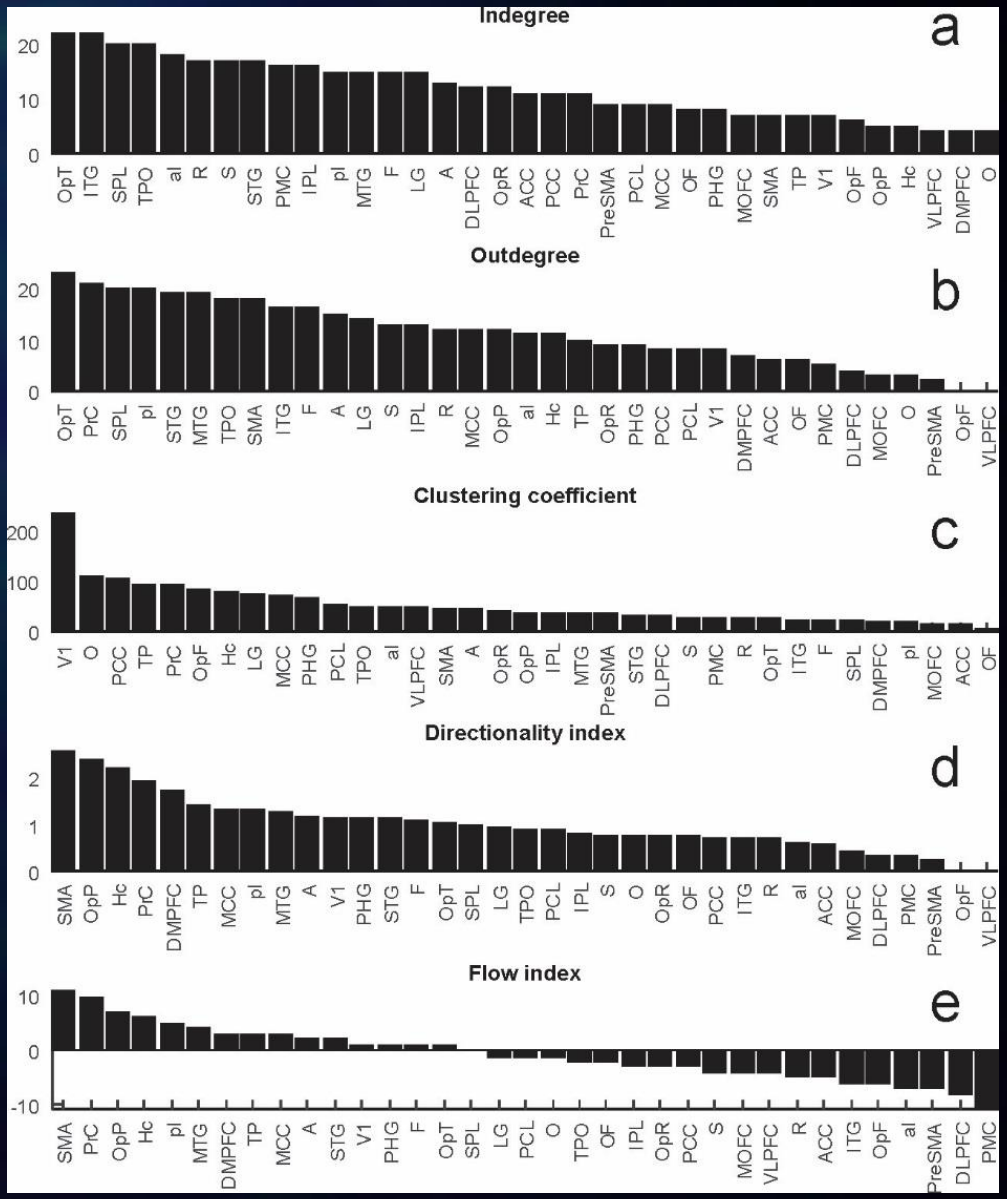
Donos C, Mălîia MD, Mîndruţă I, Popa I, Ene M, Bălănescu B, Ciurea A, Barborica A (2016). Neuroimage 132:344-358.

Network Measures

- Characterization of network topology
- Indegree/outdegree: *number of links connected to each node*
- Directed Clustering coefficient:

$$C^{\rightarrow} = \frac{1}{n}\sum_{i\in N}\frac{t_i^{\rightarrow}}{\left(k_i^{\text{out}}+k_i^{\text{in}}\right)\left(k_i^{\text{out}}+k_i^{\text{in}}-1\right)-2\sum_{j\in N}a_{ij}a_{ji}}.$$

- Directionality index:
  - outdegree/indegree
- Flow index:
  - outdegree-indegree



Donos C, Mălîia MD, Mîndruţă I, Popa I, Ene M, Bălănescu B, Ciurea A, Barborica A (2016). Neuroimage 132:344-358.

Conclusions (connectome)

- Responses to SPES can be used to calculate the effective brain connectivity.
- Effective connectivity correlates with the number of fibers connecting structures
- Mapping the effective connectivity on the number of fibers provides a structural-effective connectome of the brain
- Selection of non-pathologic structures allows to build a whole-brain physiological structural-effective connectome, that can be used as a reference connectivity atlas.

Outline

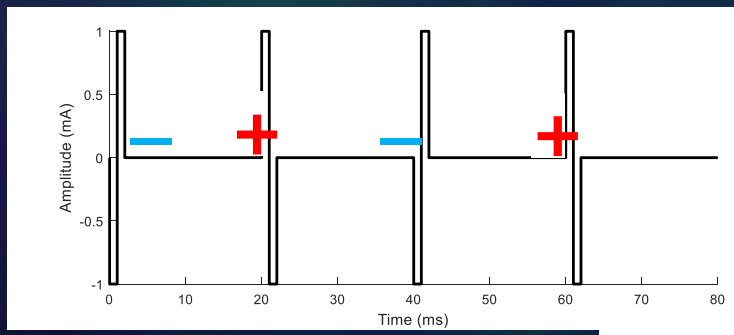
- Signal analysis methods developed and used in Bucharest for analysis of SEEG recordings:
  - Epileptogenicity biomarkers / mapping
  - Functional connectivity
- Spontaneous activity
  - Ictal: epileptogenicity indexes
- Responses to intracranial stimulation
  - Low frequency – SPES (f<0.1 Hz)
    - Biomarkers: HFO, Delayed Responses
    - Effective connectivity using CCEP – brain connectome
  - High frequency (f=50 Hz)
    - Functional connectivity during stimulation

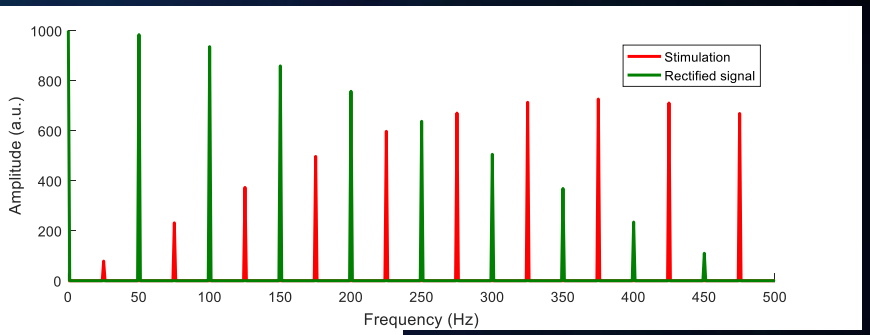
Functional Connectivity during high-frequency stimulation

- Connectivity associated with clinical symptoms
- Subtle modification of the high-frequency 50 Hz stimulation protocol allows recovery of the responses **during** stimulation
- Allows evidencing recruitment of networks related to clinical effects

50 Hz Signal Analysis

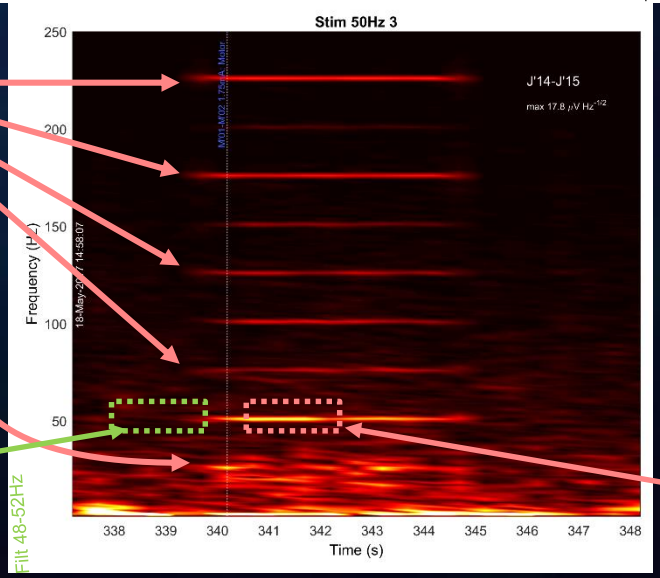
- Alternating polarity of pulses, combined with nonlinear tissue response results in non-overlapping spectral content for the responses for the artifact - fully separable components
- Modulation theorem: $\mathcal{F}\{\cos(\omega_0 t)\cdot f(t)\} = \frac{1}{2}[F(\omega-\omega_0)+F(\omega+\omega_0)]$





Artifact
25 Hz + odd order harmonics

a



Baseline R_B

1s epoch
F=48-52Hz

Modulation

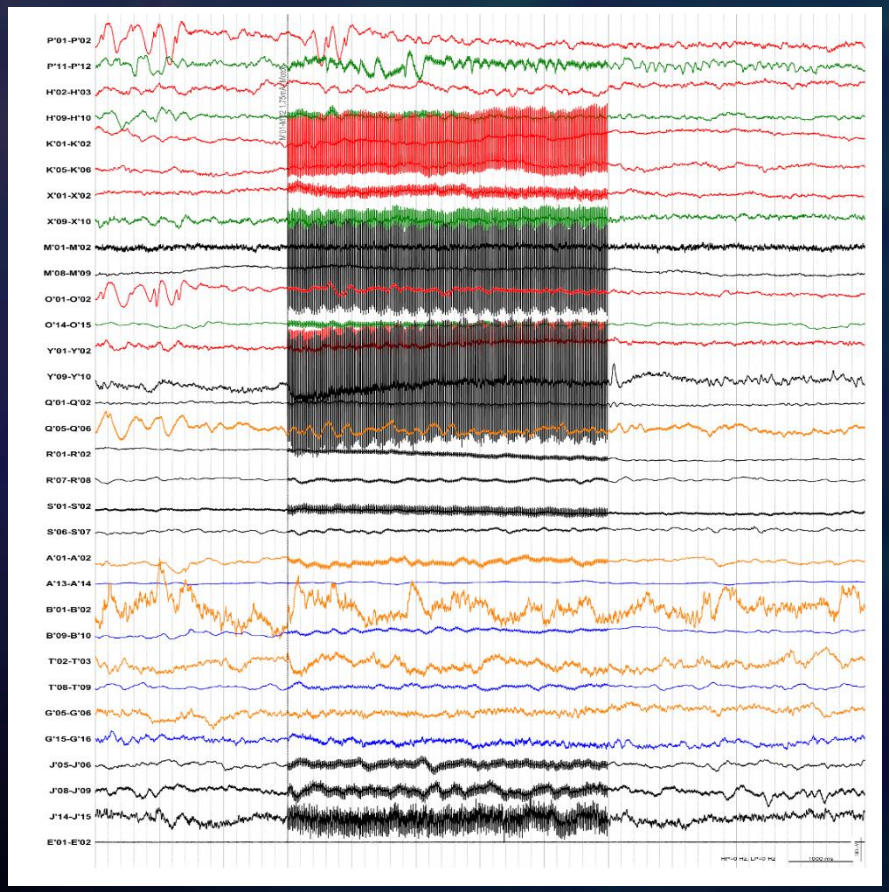
50 Hz → **75 Hz**, **25 Hz**

1s epoch
F=48-52Hz

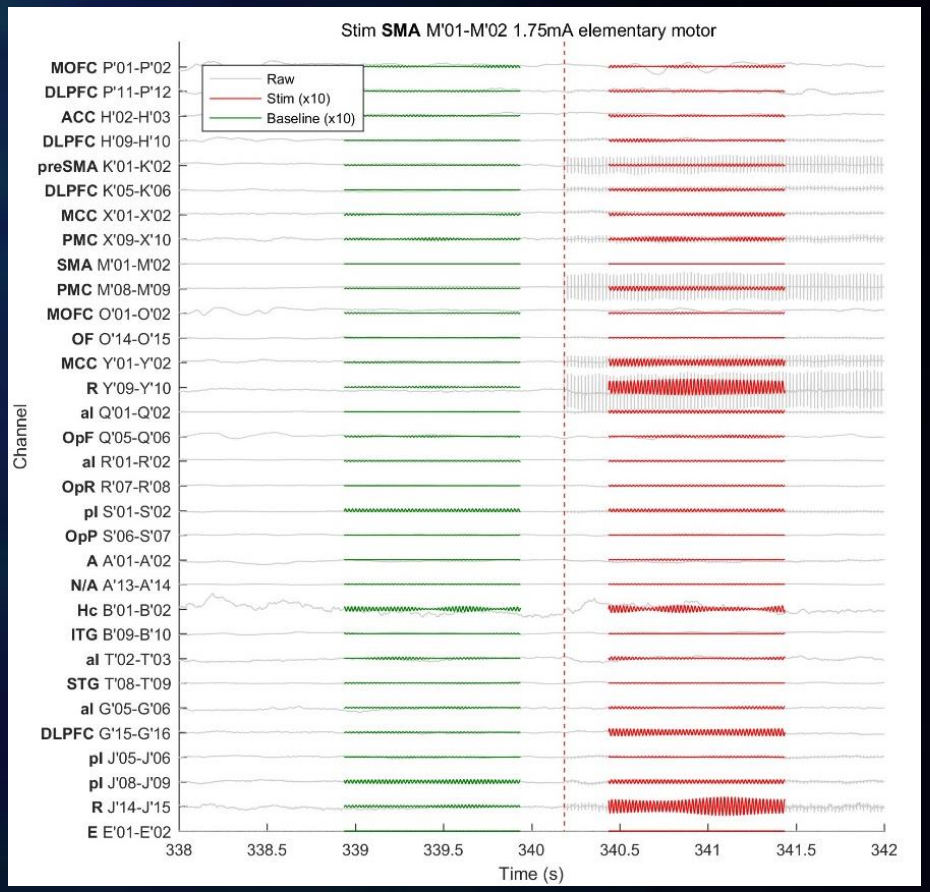
Stim Response R_S

50 Hz Signal Analysis

Raw Signal



Processed Signal

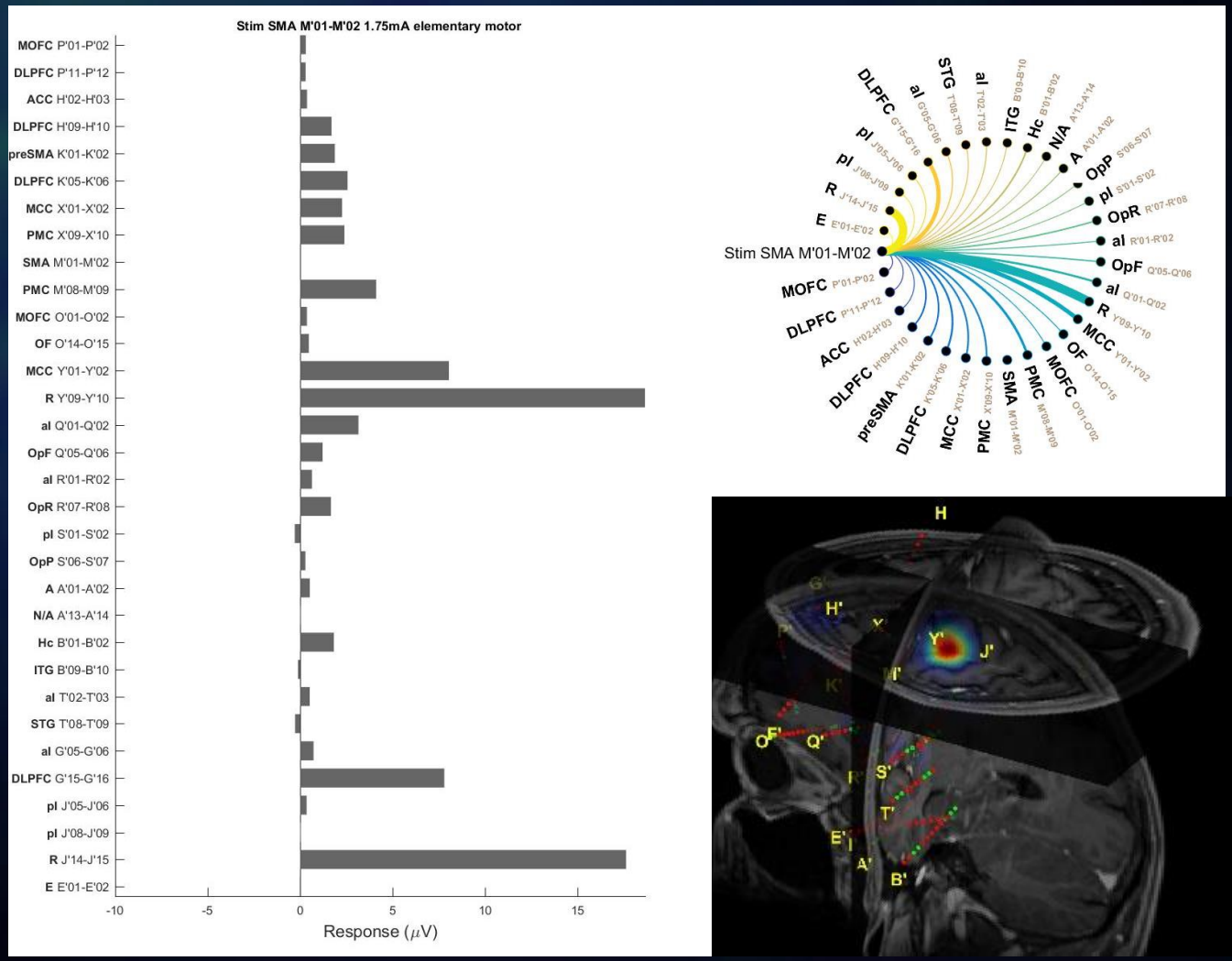


- Stimulation vs Baseline response:

$$R = R_S - R_B$$

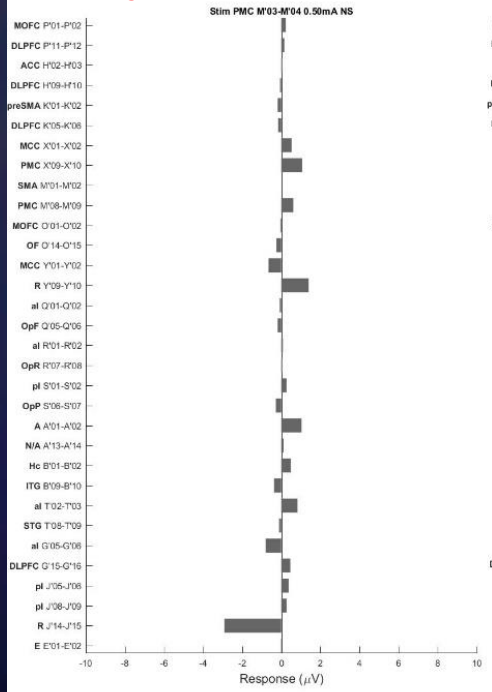
50 Hz Signal Analysis

- Response charts / diagrams

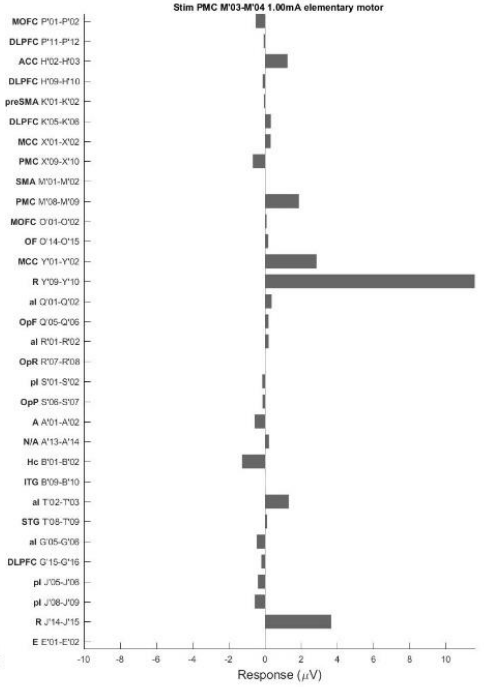


50 Hz Signal Analysis

I_{NS}=0.5 mA, no symptom



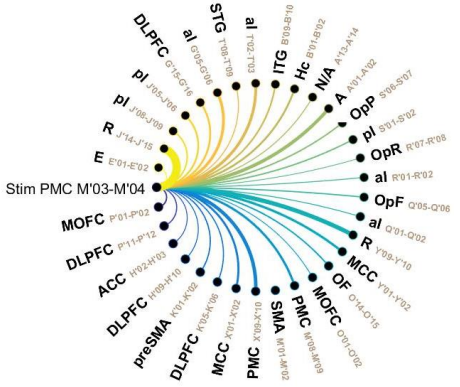
I_{SYM}=1 mA, elementary motor

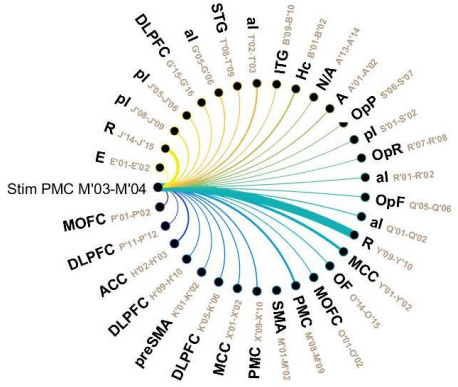


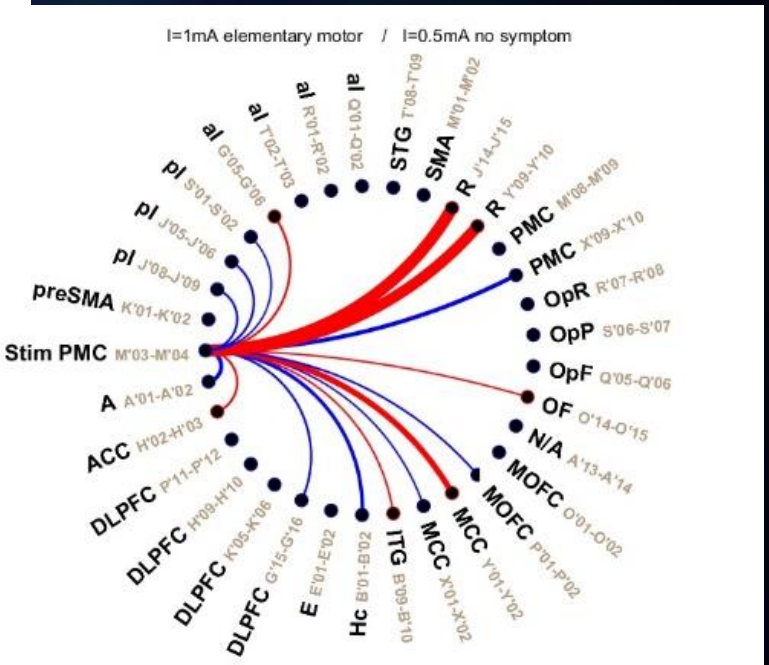
Selective network recruitment associated with a clinical effect

Activation factor:

$$AF = R^{SYM}/I^{SYM} - R^{NS}/I^{NS}$$







Conclusions (functional stimulation)

- By modulating the properties of the stimulation waveforms, in conjunction with the nonlinear response of the tissue to electrical stimulation, we were able to recover the physiological responses during the course of the stimulation train.

- This method allowed us to evidence the activation of specific pathways in the brain when a clinical symptom is evoked by electrical stimulation.

Acknowledgements

- Bucharest, Romania
  - Biophysics
    - Andrei Barborica
    - Cristian Donos
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    - Victoria Raicu

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Thank You !

Supplementary Information

Spectral properties of spikes and oscillations: Analytical description

- Modeling of HFO superimposed with spikes:
  - A Gaussian having a standard deviation σ_{sp}

$$sp(t) = a_{sp} e^{-\frac{t^2}{2\sigma_{sp}^2}}$$

    - Has as spectrum a Gaussian (centered on the origin):

$$SP(f) = A_{sp} e^{-\frac{f^2}{2\sigma_{fsp}^2}} \quad \text{where} \quad \sigma_{f_{sp}} = \frac{1}{2\pi\sigma_{sp}}$$

Faster spike, broader spectrum

  - A HFO having a frequency f_0 having as envelope a Gaussian:

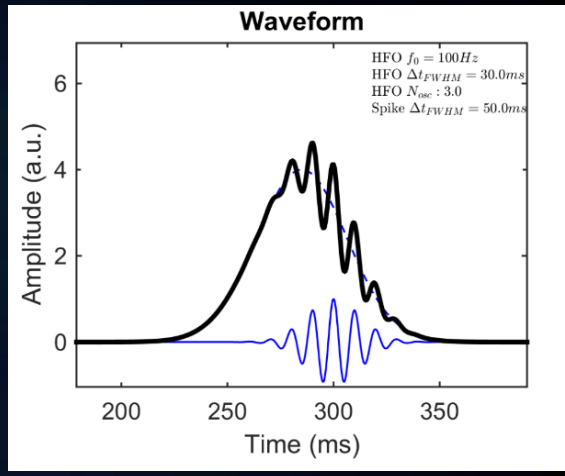
$$hfo(t) = \underbrace{a_{hfo} e^{-\frac{t^2}{2\sigma_{hfo}^2}}}_{envelope} \cdot \underbrace{\cos(2\pi f_0 \cdot t)}_{oscillation}$$

    - Has as spectrum a Gaussian centered on the frequency f_0 :

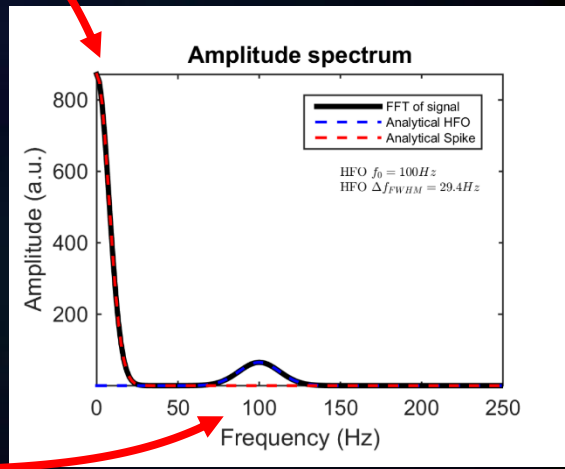
$$HFO(f) = A_{hfo} e^{-\frac{(f-f_0)^2}{2\sigma_{f_{hfo}}^2}} \quad \text{where} \quad \sigma_{f_{hfo}} = \frac{1}{2\pi\sigma_{hfo}}$$

(Modulation theorem in Fourier analysis)

Shorter HFO, broader spectrum



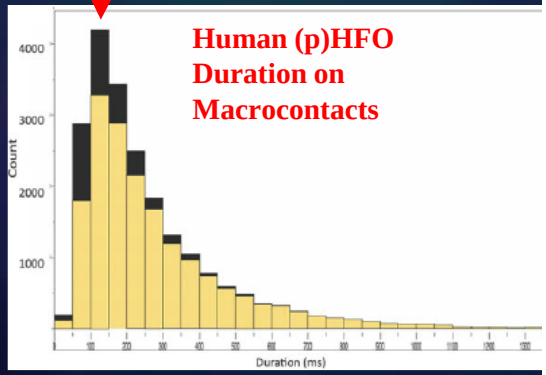
F



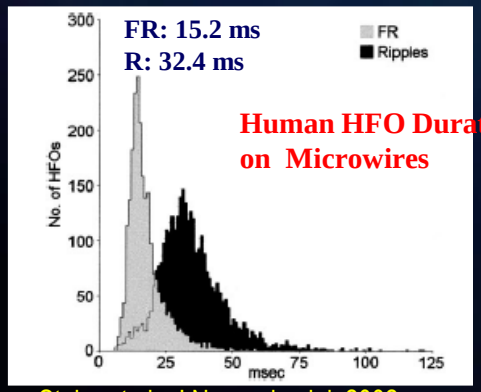
Why factor in HFO duration?

- Time-frequency (TF) representations use particular time windows for analysis that may not be appropriate for visualizing and detecting HFOs
- Example: using Morlet wavelets for TF maps – developed for *geoseismic* signals

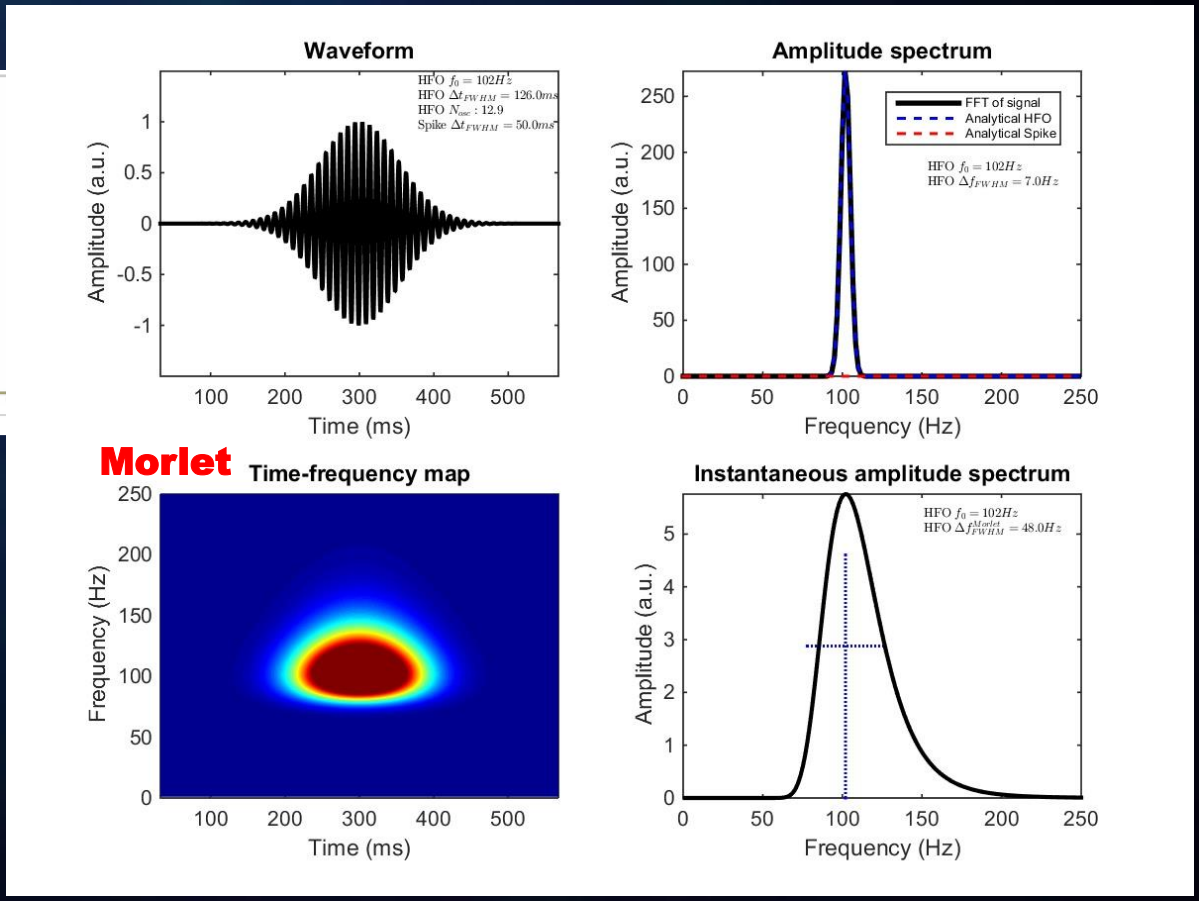
Median **Δt=126** ms



Alkawadri et al., Epilepsia, 2014

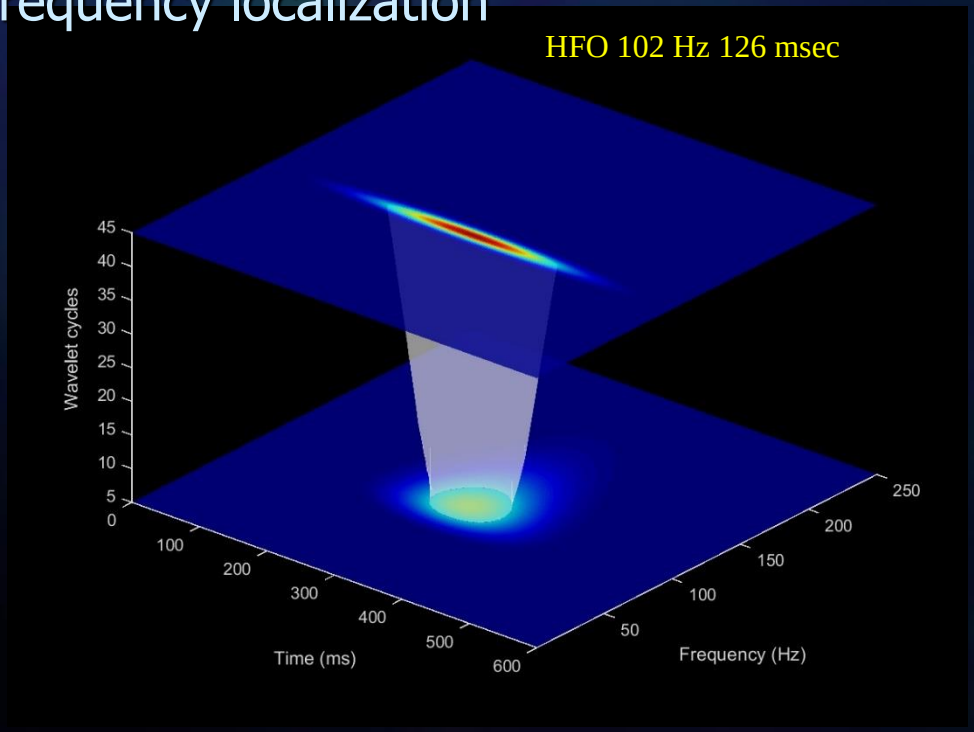


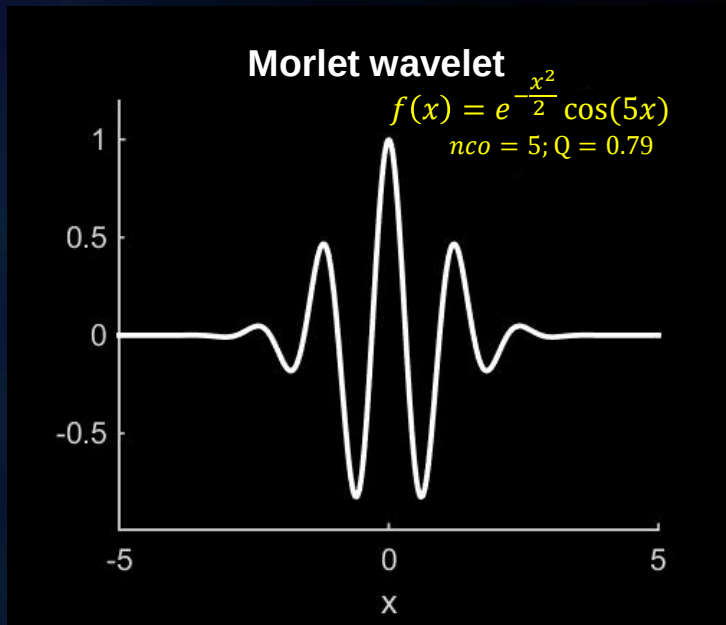
Staba et al., J Neurophysiol, 2002

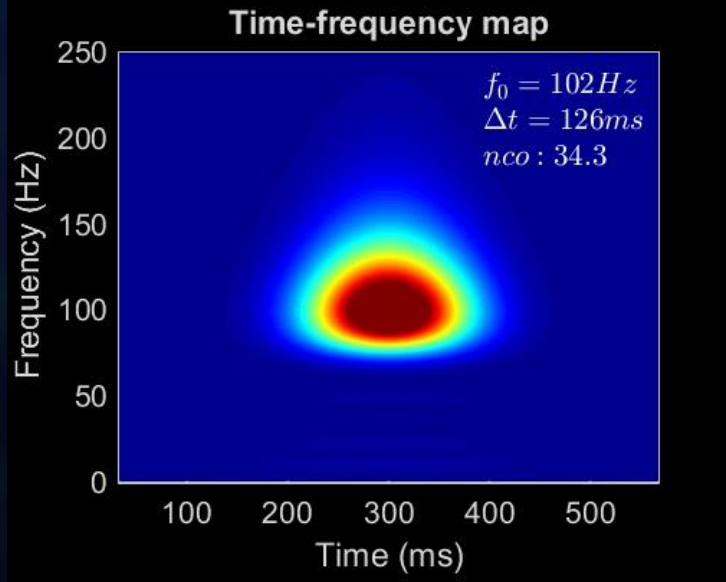


Using "standard" methods for TF maps

- Morlet wavelet is a particular type of Gabor function with a $nco = \omega\sigma = 2\pi f\sigma$ factor of 5 (number of oscillations) – poor frequency resolution
- Using Gabor functions with larger *nco* (or better Q-factor) would allow better frequency localization







Using signal-adapted wavelets

- **Matched filters** – widely used in signal processing, including EEG:

Hector Mesa, Adapted Wavelets for Pattern Detection, Progress in Pattern Recognition, Image Analysis and Applications, Volume 3773, Lecture Notes in Computer Science pp 933-944

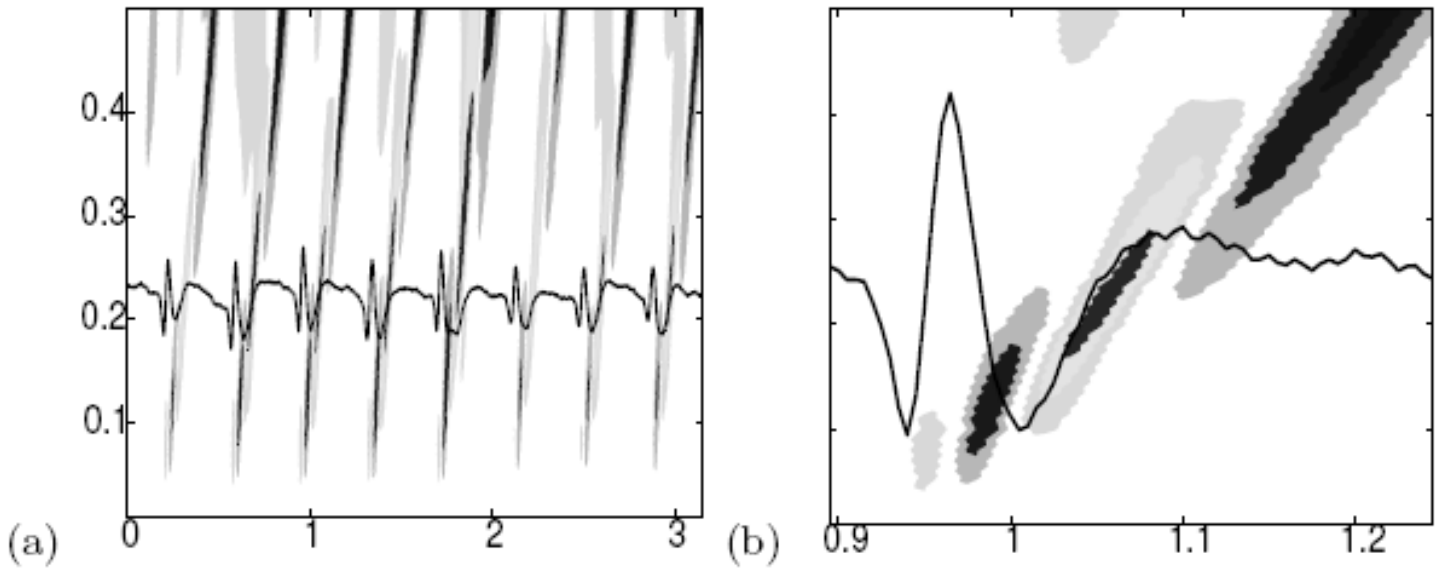
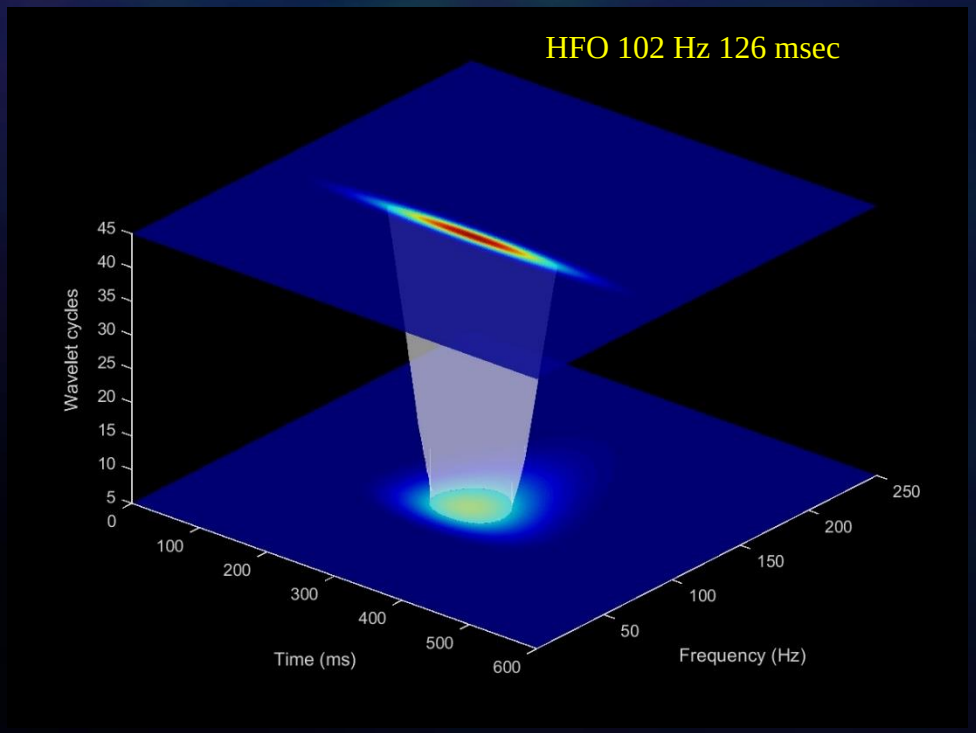
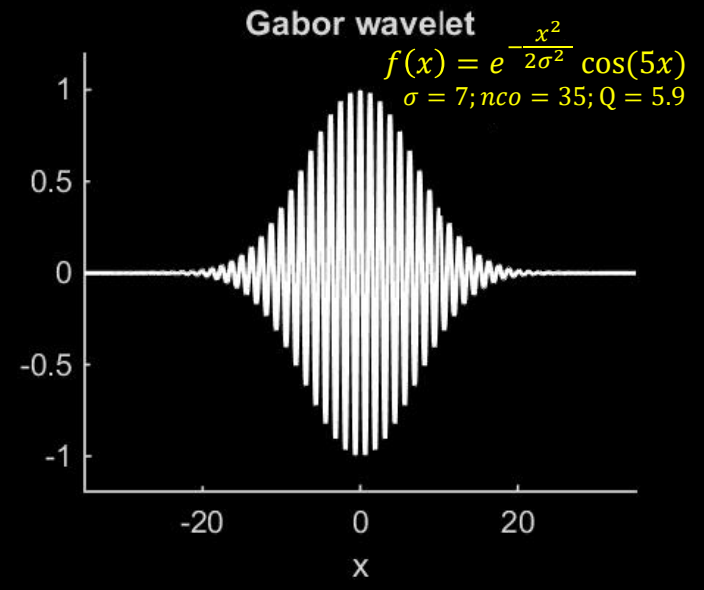


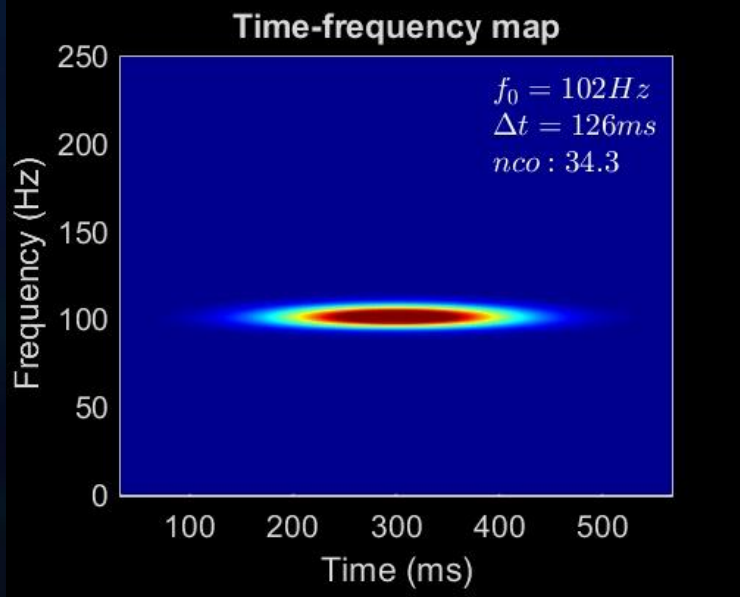
Fig. 2. (a)An EEG fragment and its CWT with the spike-wave complex adapted wavelet. (b)A zoom between .9 and 1.2s shows the existence of three local maxima of the wavelet energy around a spike-wave complex.

Using signal-adapted wavelets

- Using a Gabor function with a larger $nco \geq 35$ improves frequency resolution at the expense of poorer time resolution.
- Q: how do we combine the better time resolution at lower nco with better time frequency at higher nco?

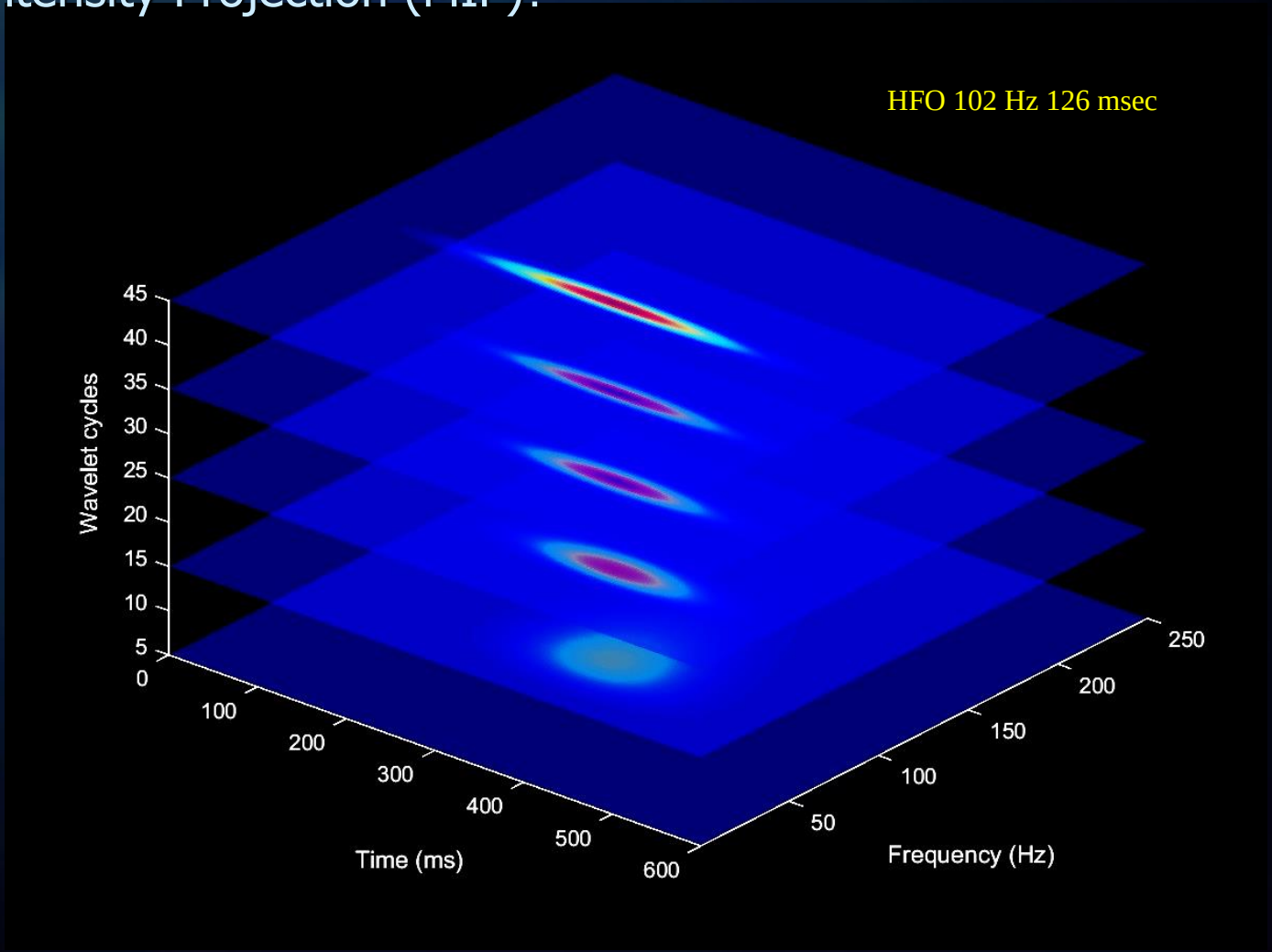






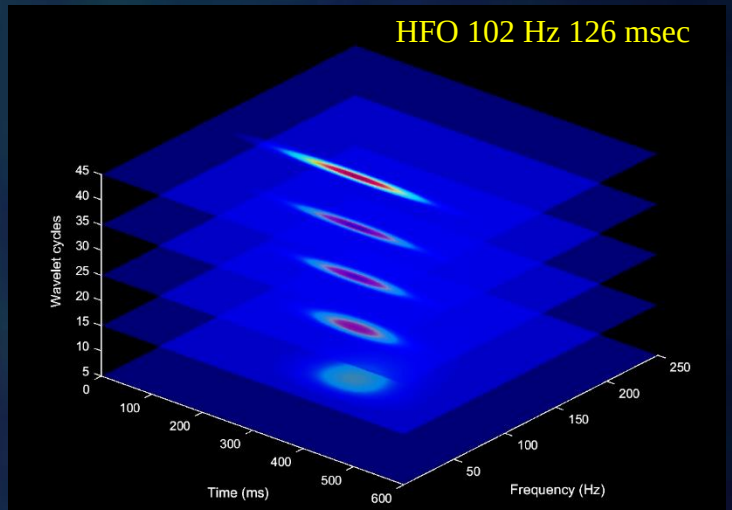
Using signal-adapted wavelets

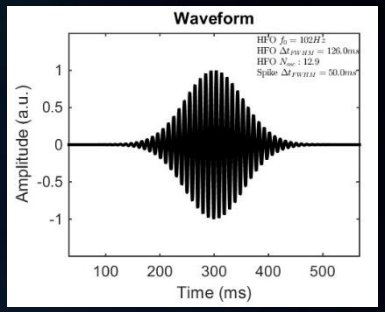
- Combining information with good time localization and frequency resolution
- Maximum Intensity Projection (MIP)?



Using signal-adapted wavelets

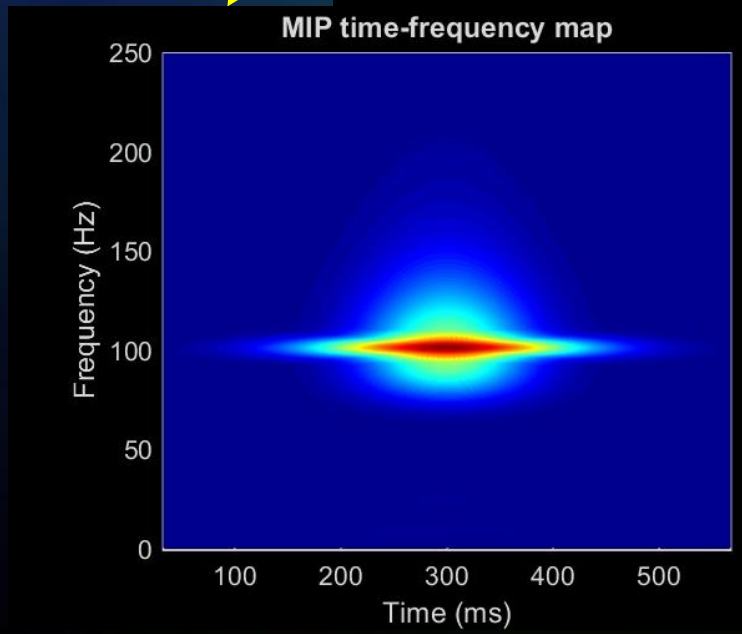
Combining information with good time localization and frequency resolution

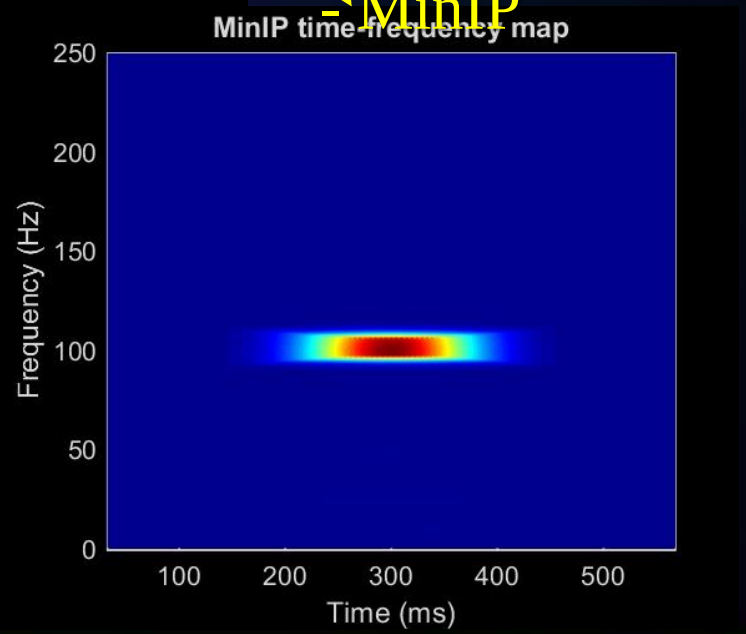




Maximimum intensity projection - MIP

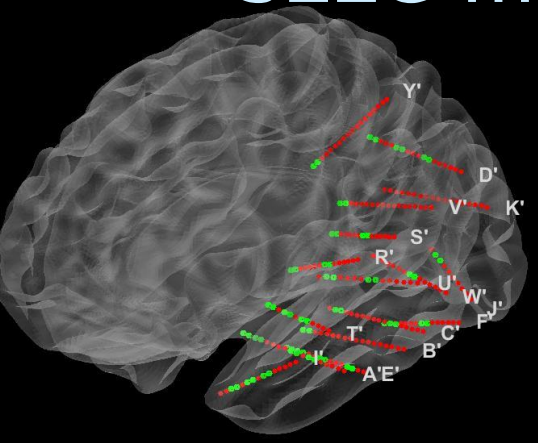
Minimimum intensity projection - MinIP





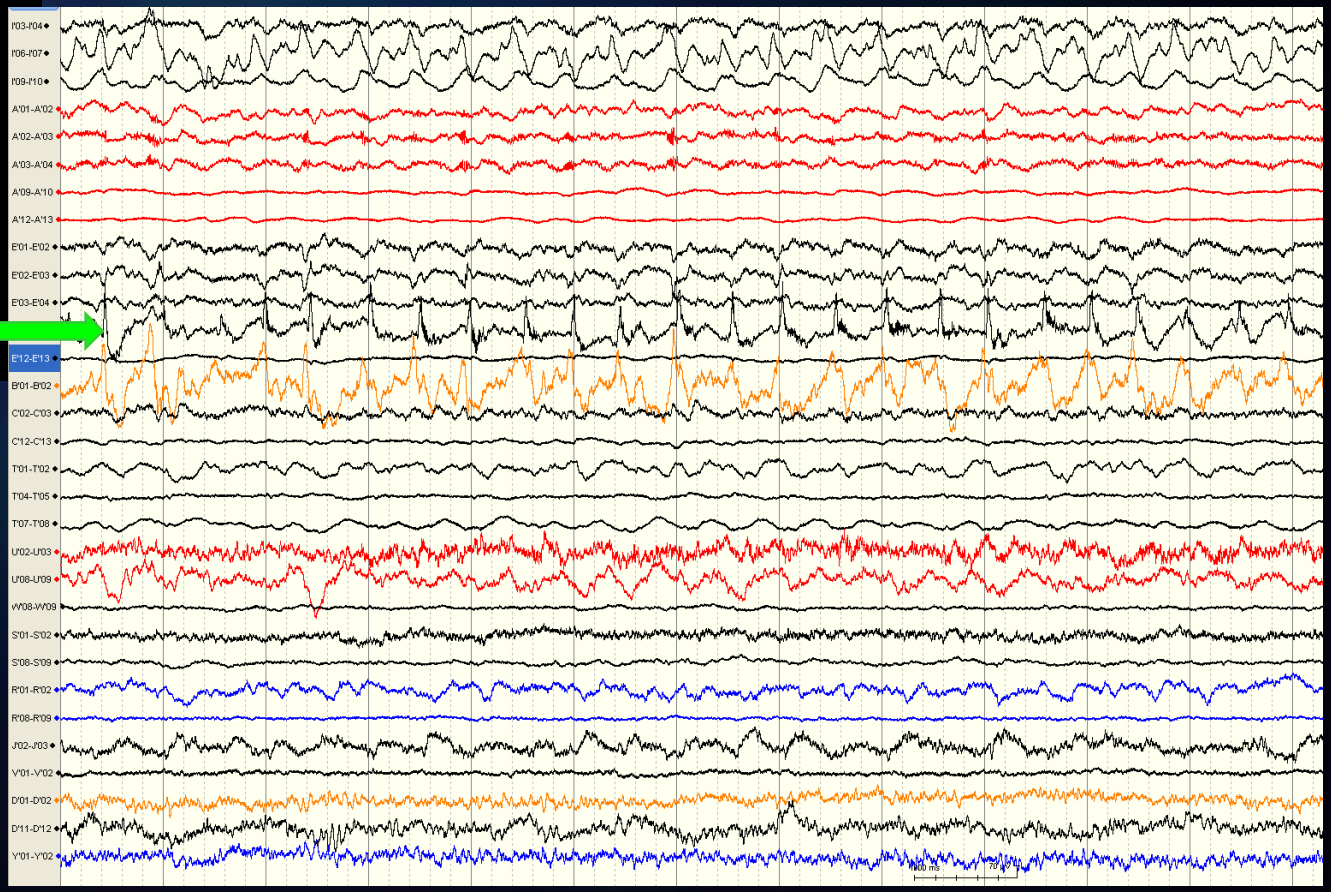
Epileptiform discharges

- Repetitive inter-ictal spikes + HFO on SEEG macrocontacts

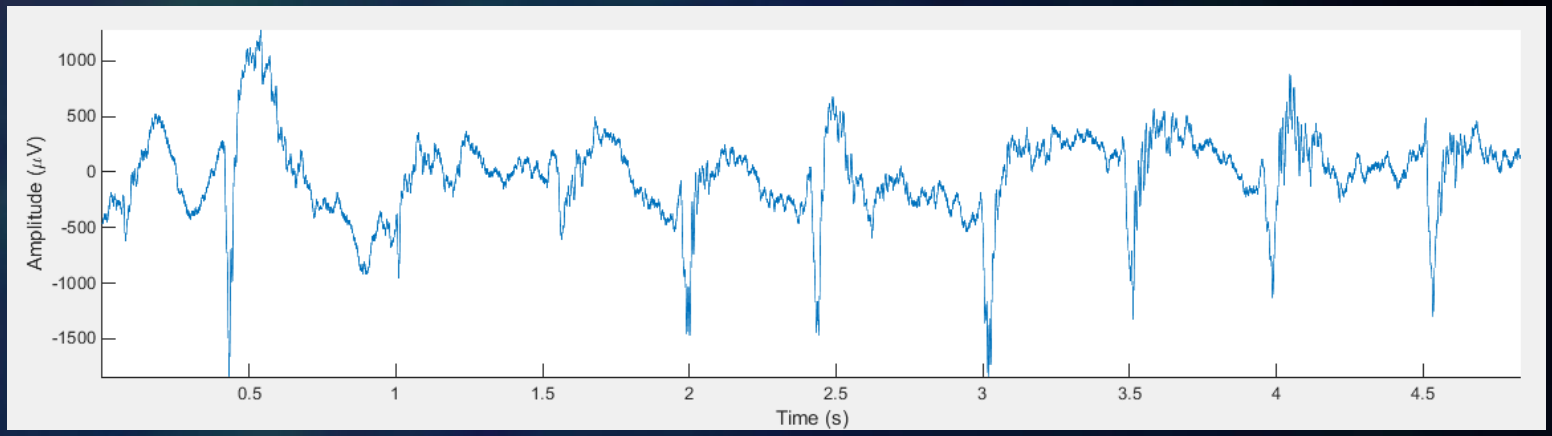


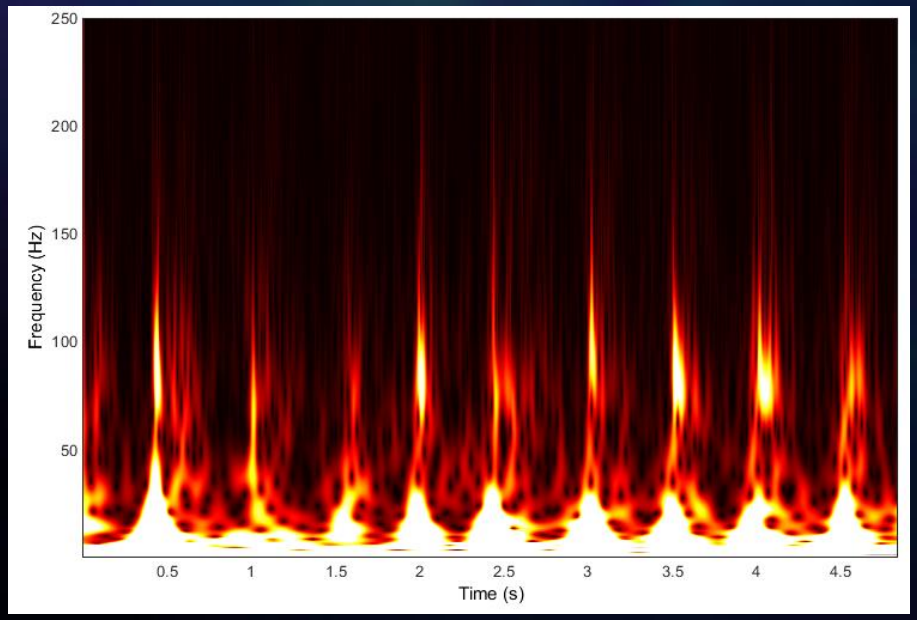
SEEG50

E'07 - inferior occipito-temporal gyrus

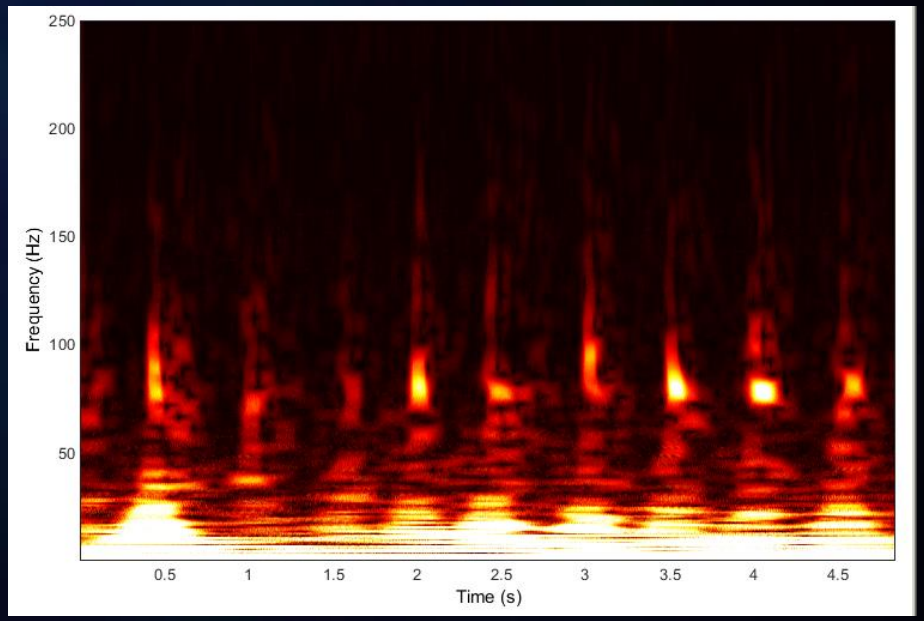


- Repetitive inter-ictal spikes + HFO on SEEG macrocontacts



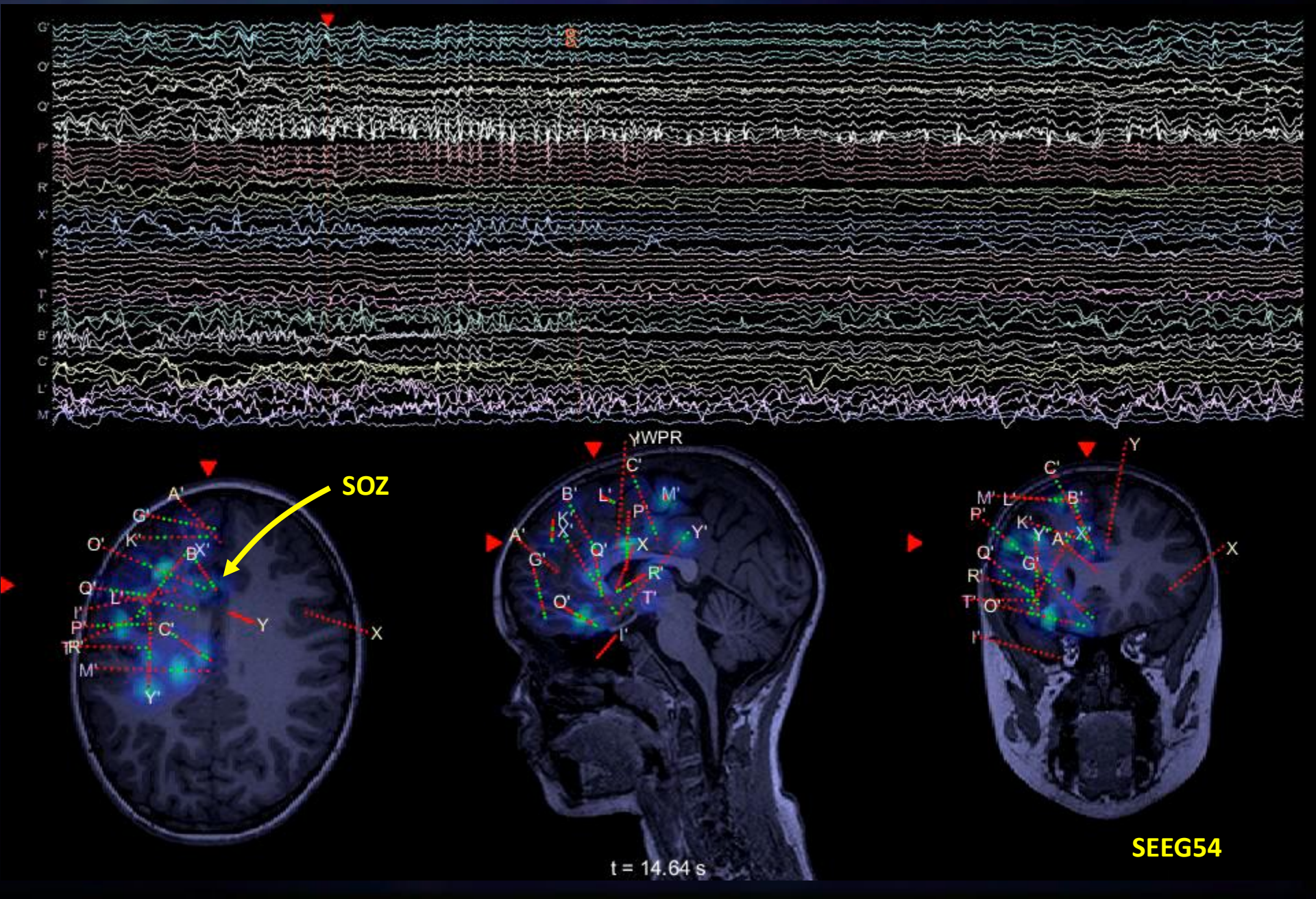


Morlet

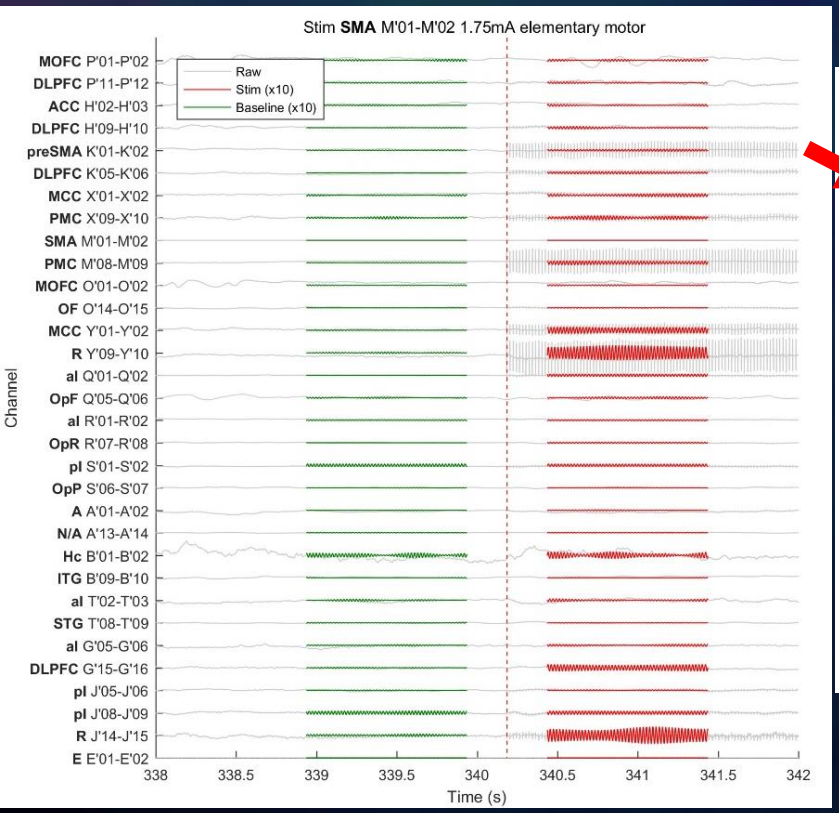


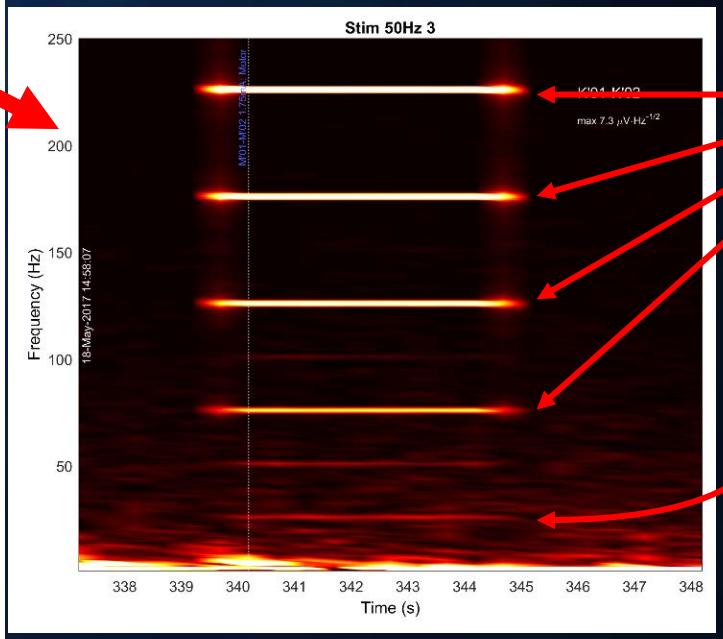
Multi-Q MinIP

Topographic mapping of IWER



50Hz Stimulation Artifact





Artifact
25 Hz + odd harmonics

Epileptogenicity Biomarkers

Percentage of positive contacts included in the resection.

Patient	Engel Score	Inbound DR	Inbound HFO	Inbound DR or HFO	Inbound DR and HFO	Outbound DR	Outbound HFO	Outbound DR or HFO	Outbound DR and HFO
1	I	28.13%	28.89%	28.13%	28.89%	31.82%	32.14%	30.00%	35.00%
2	I	18.37%	27.27%	20.37%	23.53%	27.27%	19.23%	19.23%	27.27%
3	III	28.57%	0.00%	10.53%	0.00%	0.00%	21.88%	20.59%	0.00%
4	III	21.43%	47.62%	38.71%	25.00%	0.00%	16.67%	16.67%	0.00%
5	I	25.00%	22.73%	21.74%	33.33%	100.00%	28.95%	28.95%	100.00%
6	IV	17.65%	25.00%	25.00%	15.38%	30.00%	38.89%	38.89%	30.00%
7	I	18.18%	22.58%	22.22%	16.67%	33.33%	32.00%	32.00%	33.33%
8	I	0.00%	12.00%	11.54%	0.00%	16.67%	19.23%	18.52%	20.00%
9	I	8.00%	7.14%	7.32%	8.33%	40.00%	9.76%	17.78%	25.00%
10	I	14.29%	21.43%	20.00%	9.09%	0.00%	28.57%	28.57%	0.00%
11	II	100.00%	16.67%	37.50%	100.00%	0.00%	33.33%	20.00%	-
12	I	31.25%	57.14%	33.33%	60.00%	37.14%	40.00%	36.59%	44.44%
13	I	7.55%	0.00%	7.55%	0.00%	21.43%	0.00%	18.75%	-
14	I	14.63%	0.00%	14.29%	0.00%	0.00%	0.00%	0.00%	0.00%
15	I	36.36%	-	36.36%	-	0.00%	-	0.00%	-
16	I	0.00%	25.00%	14.29%	0.00%	0.00%	0.00%	0.00%	0.00%
MEAN		**23.09%**	**20.90%**	**21.80%**	**21.35%**	**21.10%**	**21.38%**	**20.41%**	**24.23%**
SD		**23.07%**	**16.41%**	**10.62%**	**27.46%**	**26.28%**	**13.81%**	**12.24%**	**27.91%**