



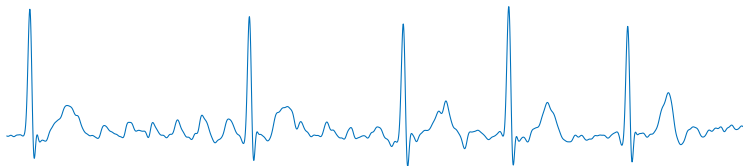
Tensor-Based Noninvasive Atrial Fibrillation Complexity Index For Catheter Ablation

Lucas de S. Abdalah, Pedro Marinho R. de Oliveira, Walter Freitas Jr,
Vicente Zarzoso

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Atrial Fibrillation

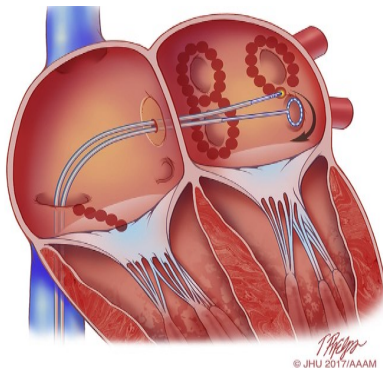
- Atrial Fibrillation (AF) is the most common sustained cardiac arrhythmia encountered in clinical practice.
 - ▶ In the EU, the number of adults with AF will double from 2010 to 2060¹.



- The complex electrophysiological mechanisms underlying AF are not completely understood.

¹Krijthe *et al.*, "Projections on the number of individuals with atrial fibrillation in the European Union, from 2000 to 2060," *Eur Heart J.* 2013.

Step-wise Catheter Ablation (CA)



- Noninvasive techniques to assess AF electrophysiological complexity can help guide step-wise CA in real time.
 - ▶ Impact of pulmonary vein isolation (PVI) and other widely used techniques on atrial activity (AA) complexity.

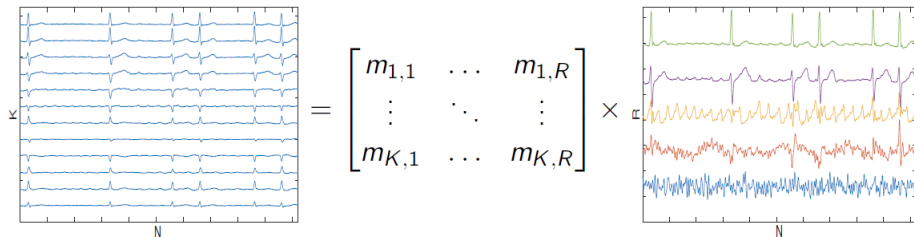
Figure from Tim Helps © 2017 Johns Hopkins University, AAM

Matrix Approach

The ECG data matrix can be modeled as:

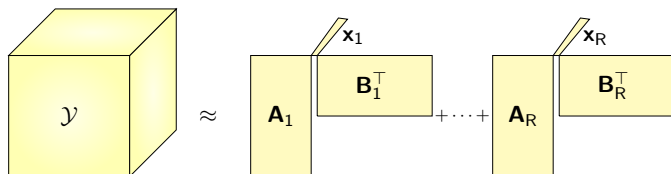
$$\mathbf{Y} = \mathbf{MS} \in \mathbb{R}^{K \times N}, \quad (1)$$

where $\mathbf{M} \in \mathbb{R}^{K \times R}$ is a mixing matrix and $\mathbf{S} \in \mathbb{R}^{R \times N}$ is the source matrix.



Tensor Approach

- The ECG data can be modeled as a 3rd-order tensor \mathcal{Y} via row-Hankelization.
 - ▶ Tensor decompositions factorize data as a sum of simpler tensors.



- Block Term Tensor Decomposition (BTD) based on Hankel structure².

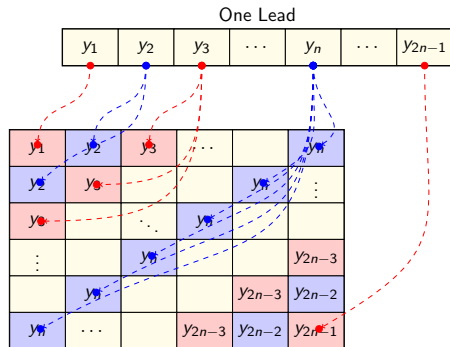
²De Lathauwer, "Blind separation of exponential polynomials and the decomposition of a tensor in rank- $(L_r, L_r, 1)$ terms," *SIAM J. Matrix Anal. Appl.*, 2011.

BTD-Hankel Model

Low-rank Hankel structure

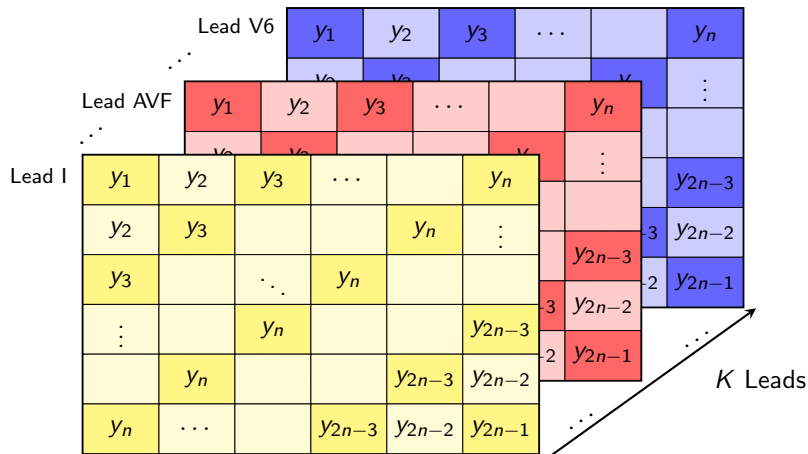
- AA signal during AF can be represented by an all-pole model (2)
- The structured Hankel matrix has a rank equal to the number of poles (L_r)

$$s(n) = \sum_{\ell=1}^{L_r} \alpha_{\ell} z_{\ell}^n \quad (2)$$

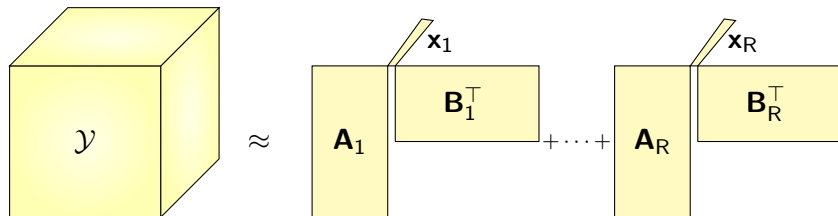


Tensor Approach

- Stack each Hankel matrix in the 3rd-mode of the tensor \mathcal{Y} .



BTD Approach



Challenge

- Parameter estimation
 - R, L_r
- Factor estimation
 - $\mathbf{A}, \mathbf{B}, \mathbf{X}$

Constrained Alternating Group Lasso

Classical BTD Approach

- Fixed structure minimizing $f(\mathbf{A}, \mathbf{B}, \mathbf{X})$ with prior knowledge of (R, L_r)

$$f(\mathbf{A}, \mathbf{B}, \mathbf{X}) \triangleq \left\| \mathcal{Y} - \sum_{r=1}^R (\mathbf{A}_r \mathbf{B}_r^\top) \circ \mathbf{x}_r \right\|_F^2 \quad (3)$$

Constrained Alternating Group Lasso (CAGL) Approach

- Non-fixed structure minimizing $F(\mathbf{A}, \mathbf{B}, \mathbf{X})$ ensuring the Hankel structure
- Penalization term (γ) and $g(\mathbf{A}, \mathbf{B}, \mathbf{X})$ limiting the multilinear ranks and number of blocks
- Allows simultaneous estimation of (R, L_r) and model factors

$$F(\mathbf{A}, \mathbf{B}, \mathbf{X}) \triangleq f(\mathbf{A}, \mathbf{B}, \mathbf{X}) + \gamma g(\mathbf{A}, \mathbf{B}, \mathbf{X}) \quad (4)$$

Signal Complexity

The more poles the signal contains, the more complex it can be considered

- The complexity index proposed in this work is based on the number of poles L_r contained in a signal.
- The Hankel matrix rank is equal to number of poles L_r .

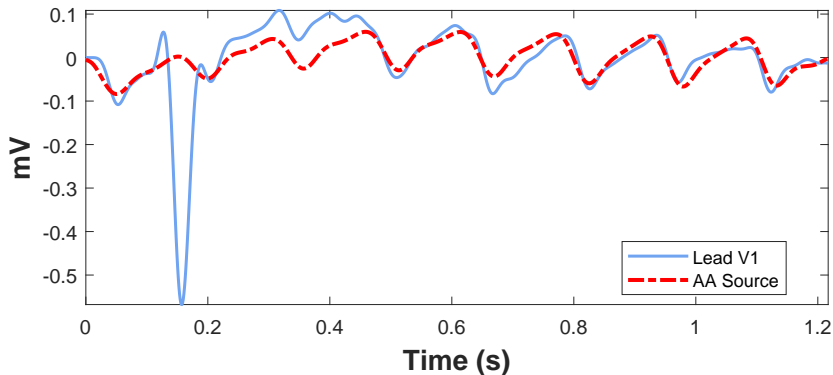
Challenge

After performing CAGL, the automated AA source classification is still a problem

- Spectral concentration (SC), dominant frequency (DF), kurtosis and visual inspection to evaluate AA extraction³.

³De Oliveira and Zarzoso, "Source analysis and selection using block term decomposition in atrial fibrillation", in *Proc. LVA/ICA*, 2018.

AA Source Estimation



- SC = 74.3%
- DF = 6.4 Hz
- Kurtosis = 177.0
- AA Hankel Matrix Rank = 33

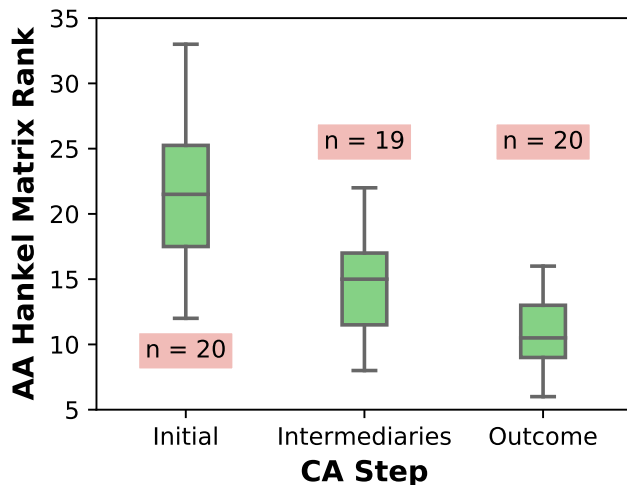
Database

- 20 patients suffering from persistent AF
- 59 ECG segments from 0.72 to 1.42 seconds

Cardiology Department of Princess Grace Hospital Center, Monaco

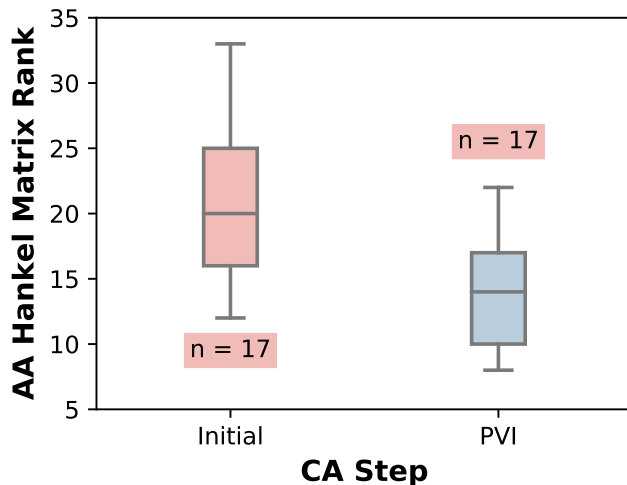
- Hankel-based BTD was implemented using CAGL.

Impact of CA step on AA complexity



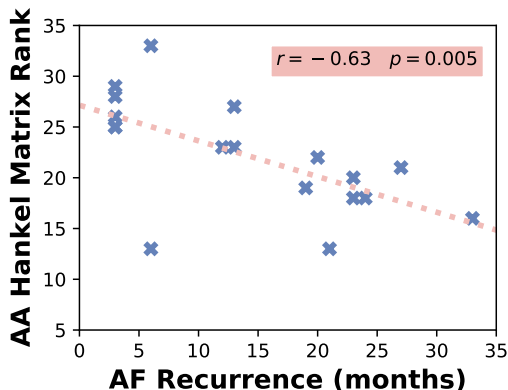
- 20 patients undergoing various CA steps
- 59 ECG segments (1.06 ± 0.2 s)

Impact of PVI on AA complexity



- 17 patients undergoing PVI
- 34 ECG segments

AF Recurrence vs. Complexity Before CA



Relationship

A significant Pearson correlation between AF recurrence and the proposed index

- 18 patients with complete follow-up information

Conclusions

Contributions

- Jointly extract the AA signal and measure AF complexity via tensor decomposition
- Very short ECG recordings (1.06 ± 0.20 s)
- Validation in 20 patients undergoing CA
 - ▶ Expected decreasing AF complexity throughout CA steps
 - ▶ Significant correlation with AF recurrence after CA

Clinical Impact

- A potential tool to help guide CA in real time

Future Work

- Increase number of patients in the database
- Compare the proposed index with other state-of-the-art indices