



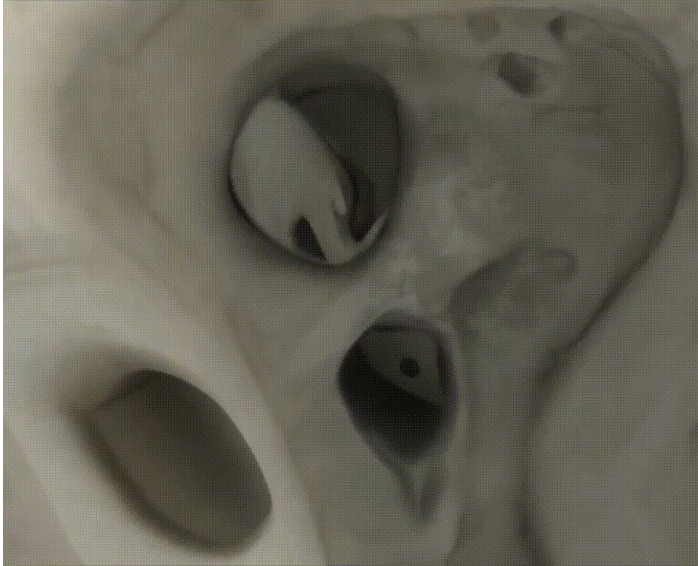
Automated Analysis of Cochlear Implant CT Images

A General Tool for Clinical Application

Celso Milne - Honours Thesis Presentation

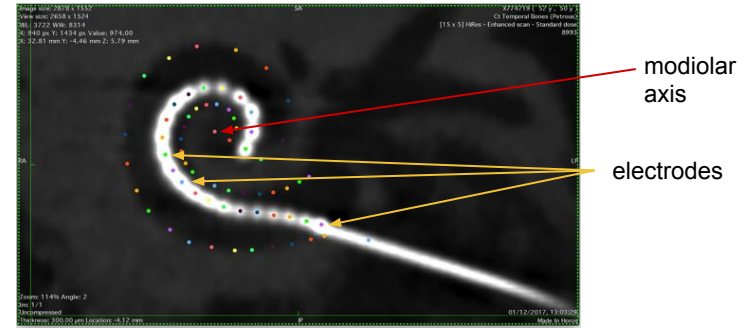
The Case For Automation

Cochlear Implant Surgery



Surgical process for CT Scans is almost completely blind, pushing a flexible electrode through the round window of the cochlea with little visual or tactile feedback [1]

Post-Op Analysis



Manually marked-up CI. Cochlear View shows metal of CI fluoresces very brightly in CT. Some tools for automated analysis exist, but their applicability is limited [2]

- Electrocochleography requires good knowledge of electrode positions & clear view of the cochlea
- This information takes > 20 minutes to obtain with current methods
- Tools for automation are very limited and rarely generalised

Research Question

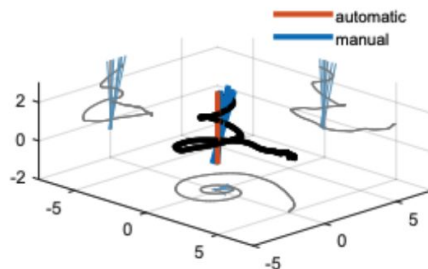
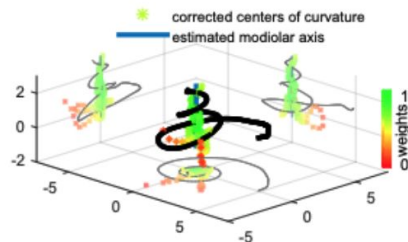
How can we create an *automated* and *extensible* tool for the analysis of *clinical* CT data in order to obtain a view of the cochlea and the locations of the electrodes and modiolar axis?

automated - as little human input as possible

extensible - to be easily used on a variety of data sources and backends

clinical - high variability of data

Previous Work



- Demarcy (2017) - 3D parametric curve fit to μ CT scans
 - Tests against 9 patients
 - All were very high resolution micro CT scans
- Fergio's tool
 - Very good starting point
 - Problems with hard coding
 - Assumes high resolution CTs in a certain orientation
 - Performance issues

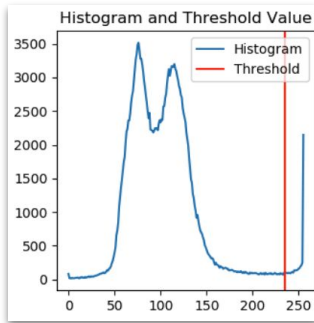
Cohen Spiral

$$f(r) = \begin{cases} c(1 - d \ln(\theta - \theta_0)) & \theta_0 \leq \theta < 100^\circ \\ ae^{-b\theta} & 100^\circ \leq \theta < \theta_{max} \end{cases}$$

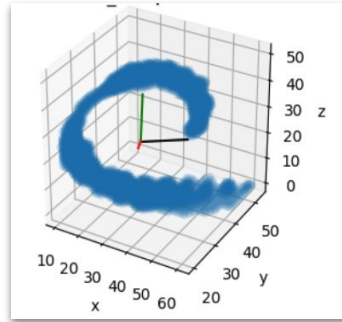
Escude Spiral

$$r = \frac{Ac}{\theta + \theta_c}$$

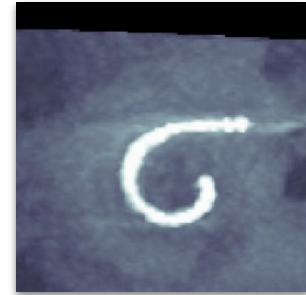
Obtaining the Cochlear View



Threshold
Segmentation on
6x6x6mm ROI



Principal Component Analysis to
obtain new reference axes

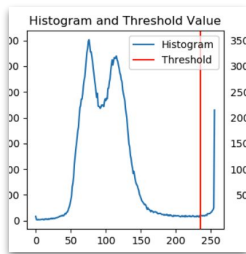


Look down new z axis to get
cochlear view

Threshold Segmentation

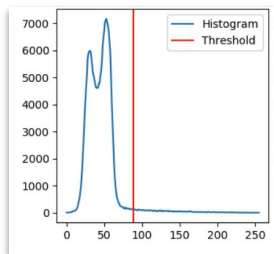
Image Types

Clipped Histogram



→ Clear peak at the tail.

Non Clipped Histogram



→ No tail peak

Control

$$\max \sum_{i=1}^k m_i$$

Maximum edge value of the histogram

Otsu [3]

$$\min_t (\omega_0(t)\sigma_0^2(t) + \omega_1(t)\sigma_1^2(t))$$

Minimize the intra-class variance of the histogram for a given threshold, t .

Modal [4]

$$\arg \max \left(\left[\arg \min_{\mathbf{S}} \sum_{i=1}^k \sum_{\mathbf{x} \in S_i} \|\mathbf{x} - \boldsymbol{\mu}_i\|^2 \right] \forall \mathbf{S} \in \mathbf{S} \right)$$

K-means clustering the image voxels into $k=5$ clusters based on their intensity. Use the maximum cluster center as t .

Simulated Annealing [5]

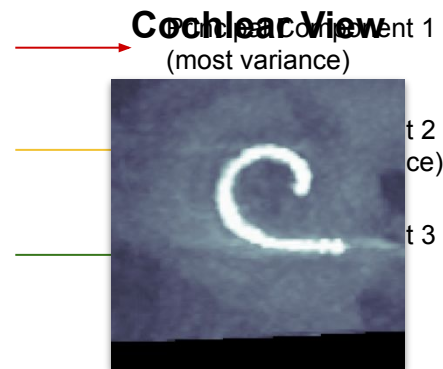
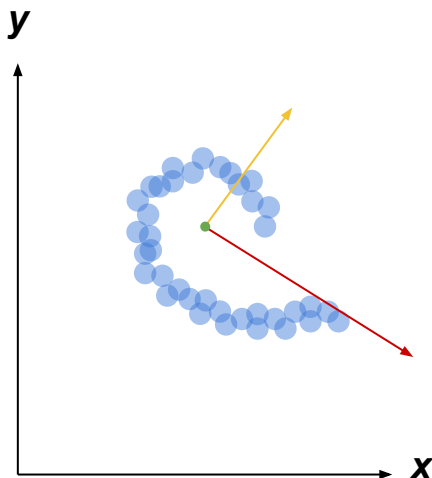
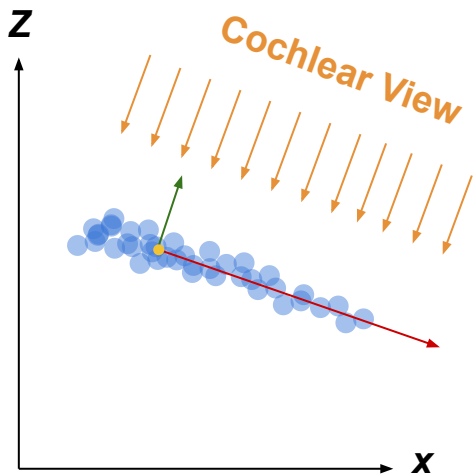
$$\max_t \left(MI(I, S_{n,t}) = \sum_{i=1}^n \sum_{j=1}^n p_{ij} \log \frac{p_{ij}}{p_i p_j} \right)$$

Maximize mutual information between the image, I , and the n -cluster segmented image, $S_{n,t}$ using a simulated annealing algorithm.



Principal Component Analysis (PCA)

- Find three orthogonal vectors through the segmented electrode points which account for the most variance using PCA, giving a new coordinate system.
- Axis of least variance is the modiolar axis
- Affine rotation about the center of the spiral to align the reference frame with the PCA vectors, then take max pixel intensity looking through the new **z** axis.



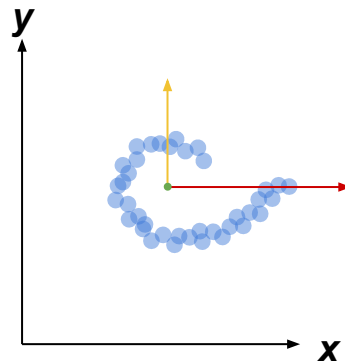
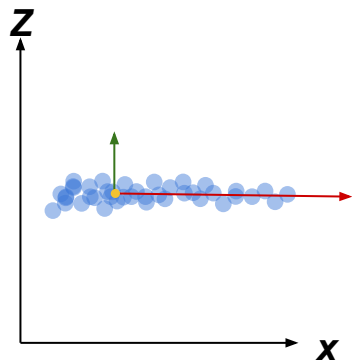
Rotation

Define Affine Rotation

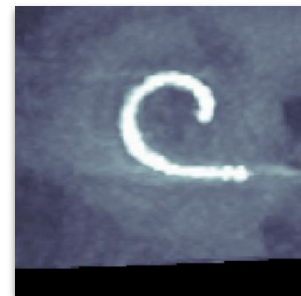
PCA Vector: $\mathbf{v}_i = \begin{bmatrix} v_{i,x} \\ v_{i,y} \\ v_{i,z} \end{bmatrix}$

$$\mathbf{R} = \begin{bmatrix} v_{1,x} & v_{2,x} & v_{3,x} & 0 \\ v_{1,y} & v_{2,y} & v_{3,y} & 0 \\ v_{1,z} & v_{2,z} & v_{3,z} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Align Coordinate Axes



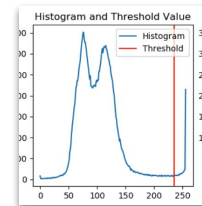
Attain Cochlear View



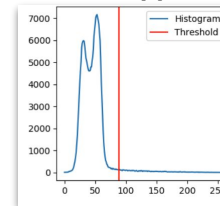
Evaluating Results

- Results manually evaluated for each method on a six point (0-5) scale.
- 45 images tested from clinical database - high variability.

Clipped

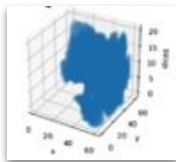


Non Clipped

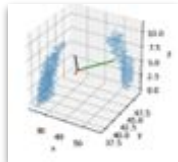


Segmentation
Ranking

0



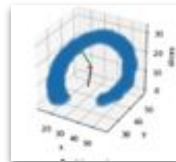
1



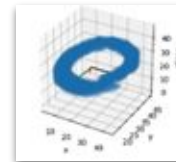
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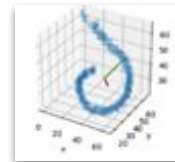
3



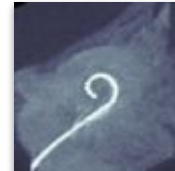
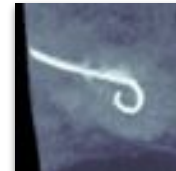
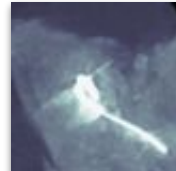
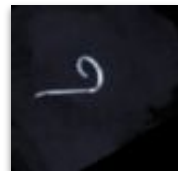
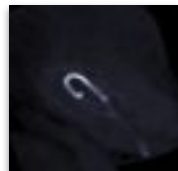
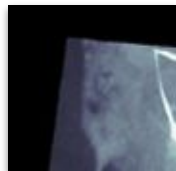
4



5



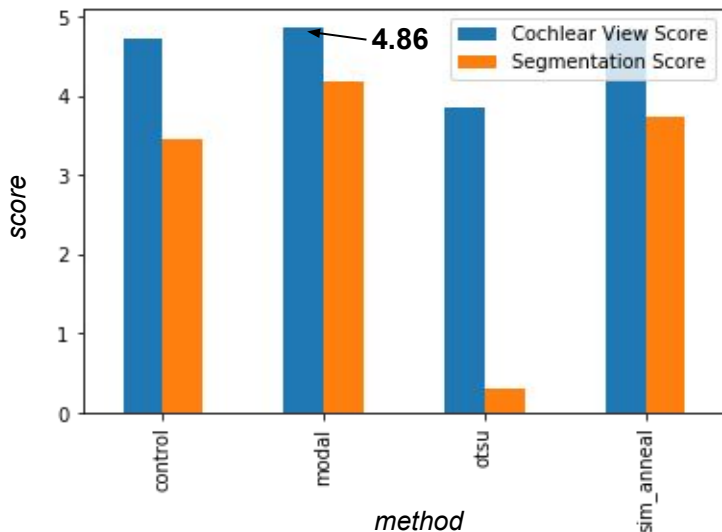
Cochlear View
Ranking



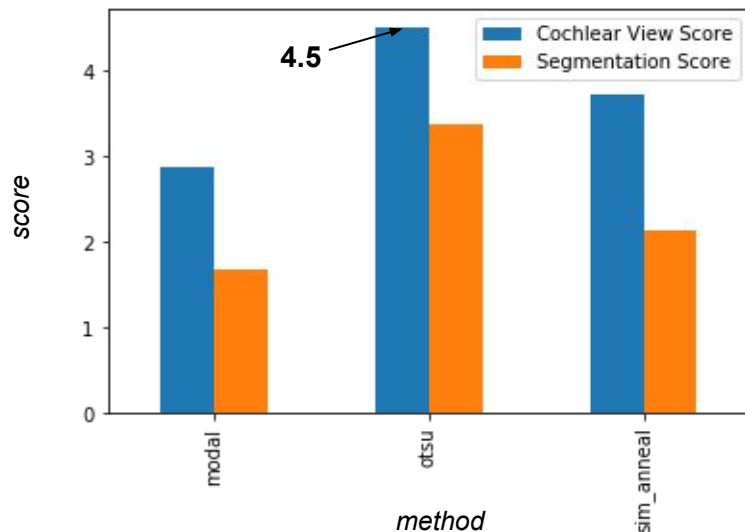


Results

Segmentation and Cochlear View on Clipped Images

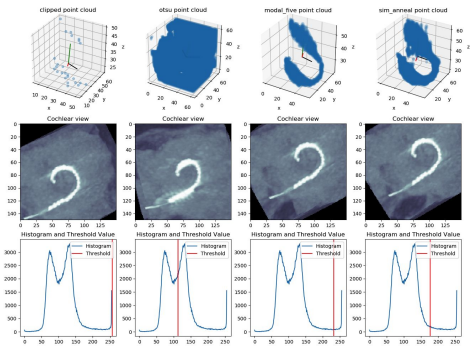
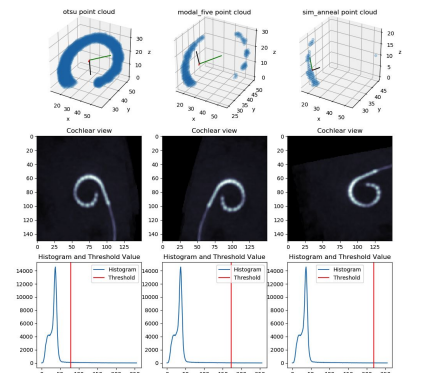
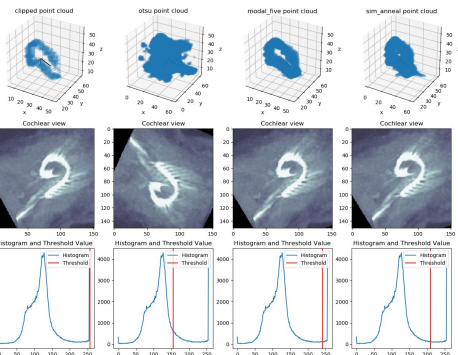
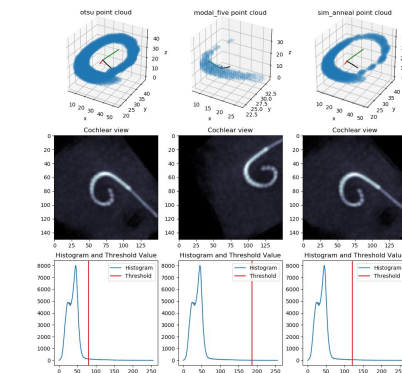
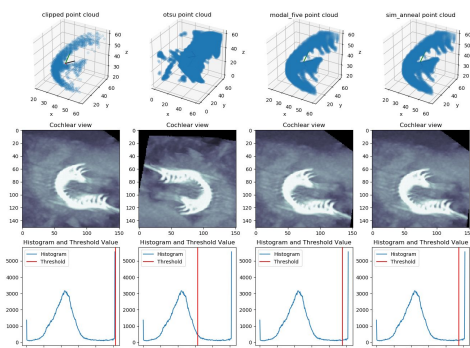
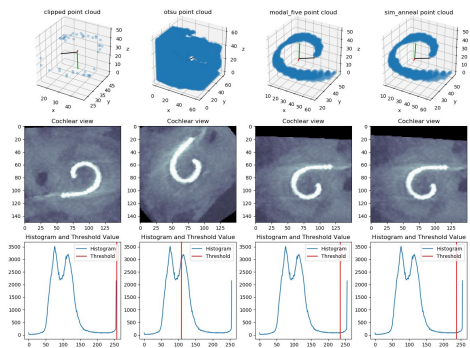


Segmentation and Cochlear View on Non-Clipped Images



-
- Very few false positives - highly extensible and reliable tool which can be used in variety of contexts
 - Robust against high variability of clinical data

Cochlear Views



Interpolating Electrode Positions

Image
preprocessing



Create PAG and
interpolate electrode
positions

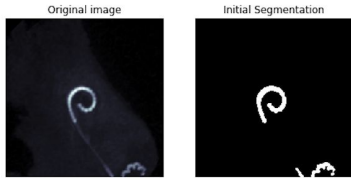


Fit modified cohen
spiral using EDRem
to find modiolar axis

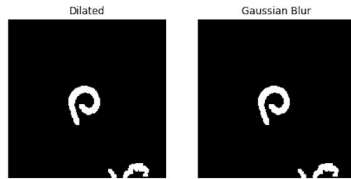


Preprocessing

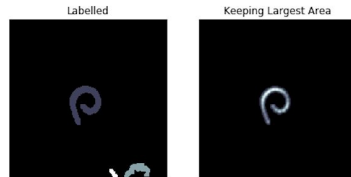
- *Goal: from a cochlear view, segment the electrode spiral*



Use modal segmentation on clipped images and otsu segmentation on non clipped images.



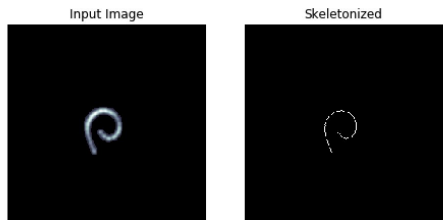
Dilate the segmentation to join broken regions in the spiral, then Gaussian blur to soften edges (5x5 kernel).



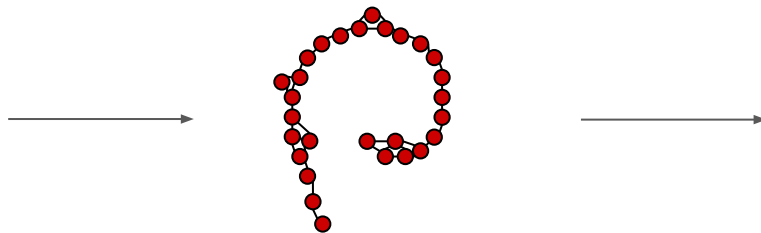
Label regions of the binary image and extract the region with the largest area - this is the electrode spiral.



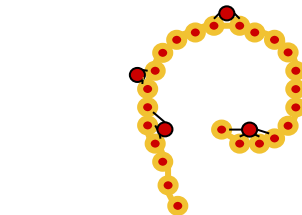
Pixel Adjacency Graph



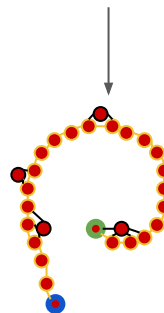
Medial axis of the segmented image is found (skeletonized)



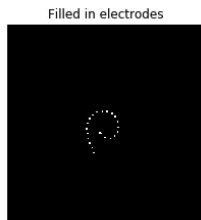
Pixel Adjacency graph.



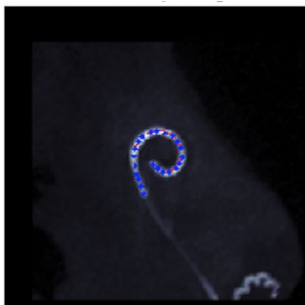
Longest path through the graph



Extreme points. Apical electrode (green).

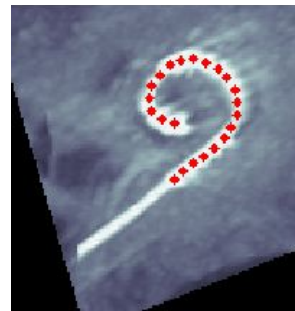
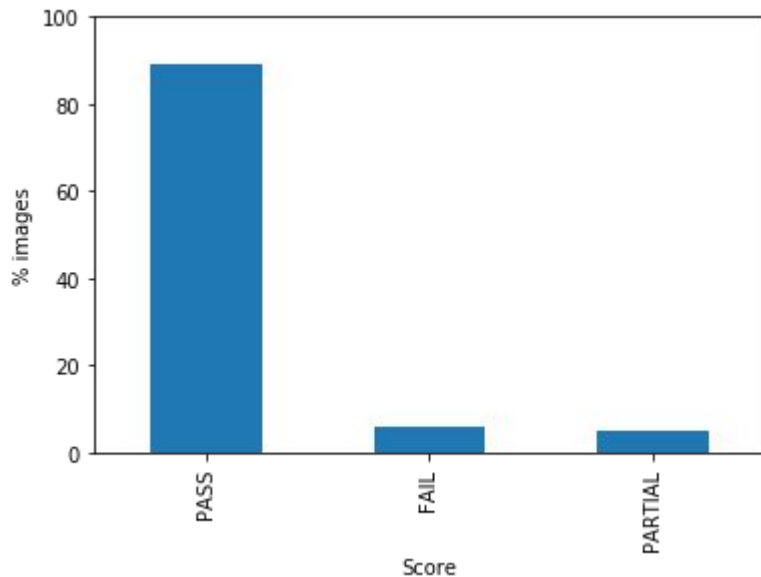


Interpolate 22 electrodes at given spacing backwards along the electrode.

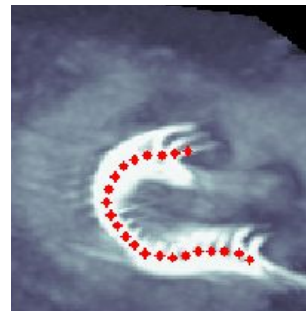


Results

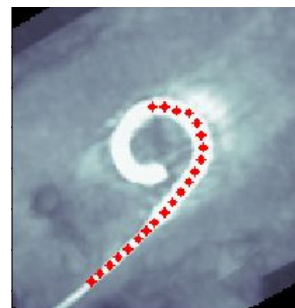
Given a valid cochlear view, a good interpolation of electrode positions was attained 89.3% of the time



Good cochlear view and electrode position interpolation (90% of cases)



Starburst throws off PAG construction



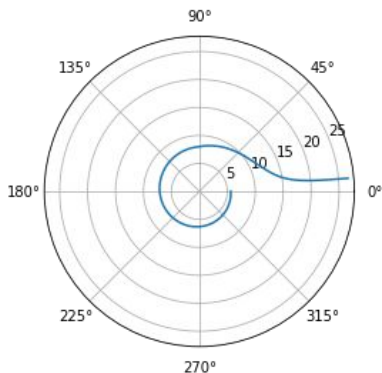
Failed images usually occur because preprocessing creates a bridge between the apical tip and the tail of the electrode, meaning longest path is incorrectly identified.



Modified Cohen Spiral

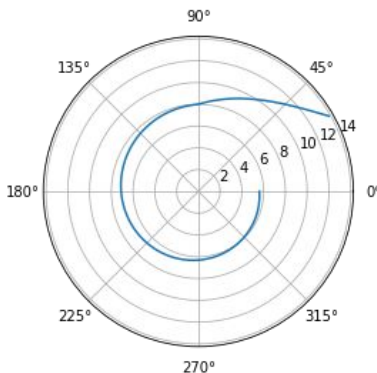
Nominal Cohen Spiral [6]

$$f(r) = \begin{cases} c(1 - d \ln(\theta - \theta_0)) & \theta_0 \leq \theta < 100^\circ \\ ae^{-b\theta} & 100^\circ \leq \theta < \theta_{max} \end{cases}$$



Modified Cohen Spiral

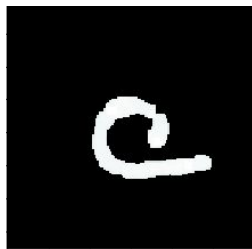
$$f(r) = \begin{cases} \frac{c}{\sqrt{\theta}} & \theta_0 \leq \theta < 100^\circ \\ ae^{-b\theta} & 100^\circ \leq \theta \leq \theta_{max} \end{cases}$$



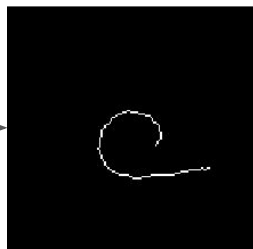
- Original spiral fits the shape of the electrode in design, but does not always reflect reality.
- Modified spiral more closely follows Escude Spiral at the tail [7].
- Spirals fit by minimizing the SSR between the modified spiral and the segmented electrode - EDReM



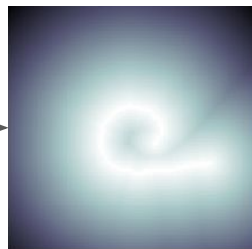
Euclidean Distance Residual Minimization (EDReM)



Input: preprocessed segmentation



Skeleton: medial axis of the input



EDT: each pixel takes value of the min Euclidean distance to the spiral

Residual Score

$$\text{score} = \sum_{i,j \in l,w} \left(\frac{C_{i,j} E_{i,j}}{n} \right)^2$$

C = Cohen matrix

E = Euclidean distance transform of the skeleton

n = arc length of C in pixels

l, w = length and width of both C and E in pixels

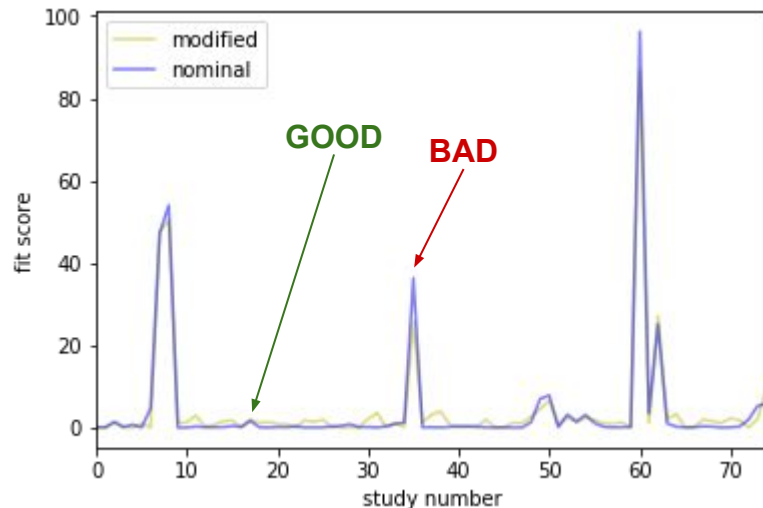
Minimization Procedure:

1. Guess initial spiral center at centre of mass of the spiral;
2. Create the cohen spiral at a given apex, rotation and size as a matrix of 1s (the spiral) and 0s (not the spiral);
3. Calculate the residual as above;
4. Step in direction of greatest decrease in score by changing rotation, center and size dimension (a);
5. Repeat 2-4 until minimum is reached.



Results

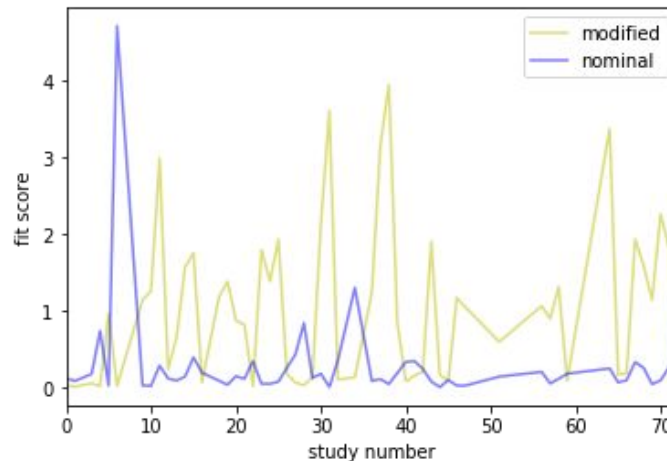
All Images



Mean fit score:

modified	4.5
normal	4.3

Consider only 'Good' Fits (Fit Score < 0.5)



Mean fit score:

modified	1.02
normal	0.31



Results

Performance

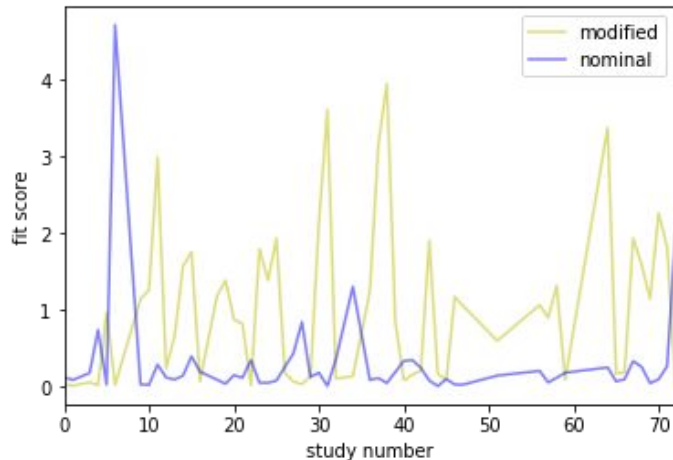
Nominal: 68.0% good fit

Modified: 30.7% good fit

Combined: 74.7% good fit

- Negative correlation coefficient suggests that several of the poor fits from one type of spiral are good for the other type

Consider only 'Good' Fits
(*Fit Score < 0.5*)



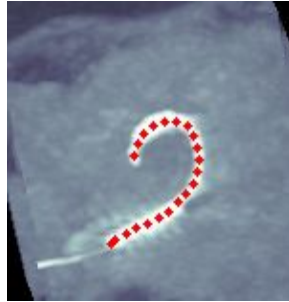
Mean fit score:

modified	1.02
normal	0.31

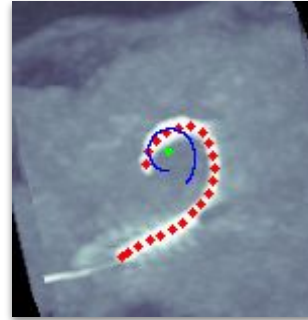
Results

***Electrode Hits the
Lateral Wall***

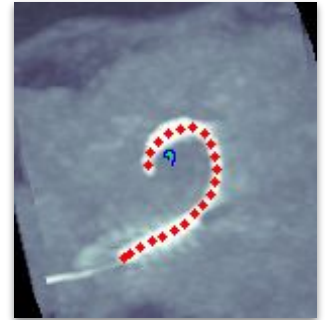
Electrode Path



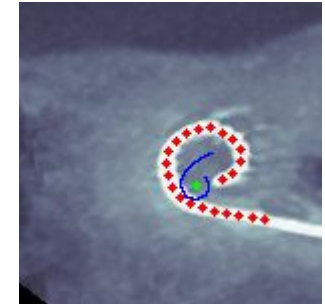
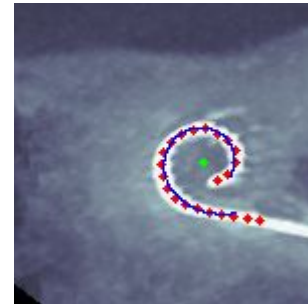
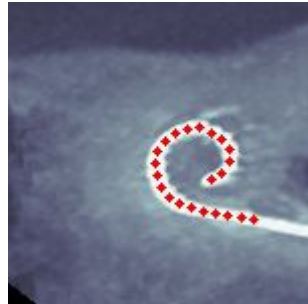
Nominal



Modified



Good Fit

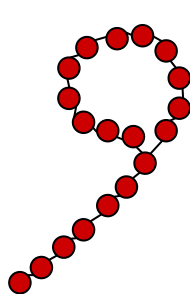


Broken Electrode Paths

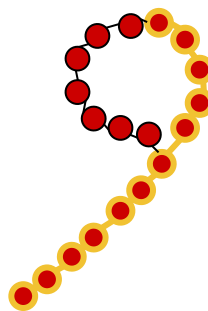
- Errors in preprocessing create a bridge between spiral and the lead wire



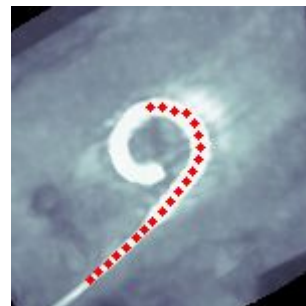
Dilation and blurring
merge regions



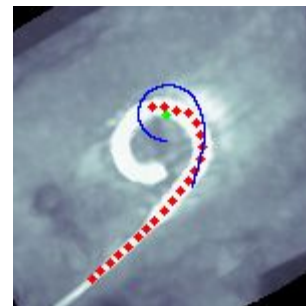
Bridge forms
between spiral and
lead wire



Electrode path
incorrectly found

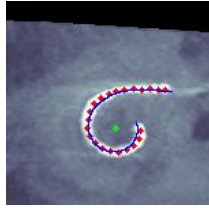


Incorrect electrode
positions

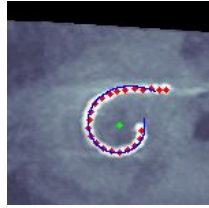


Bad Cohen Spiral fit

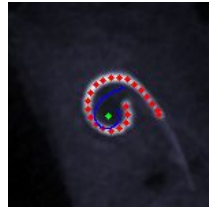
Electrodes and Modiolus



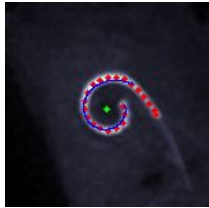
Modified



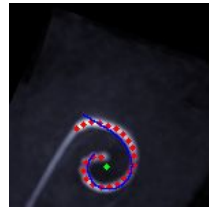
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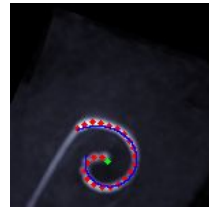
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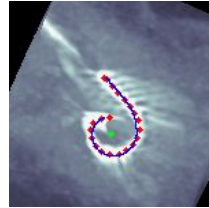
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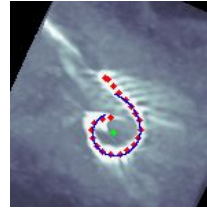
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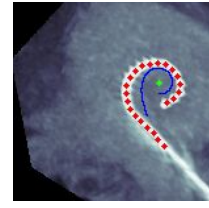
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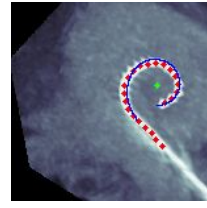
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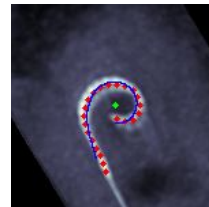
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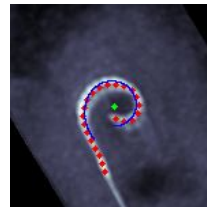
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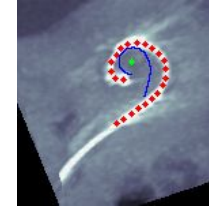
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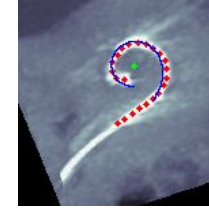
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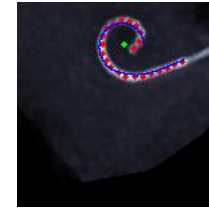
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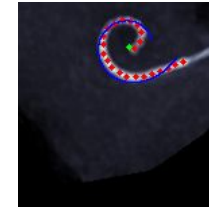
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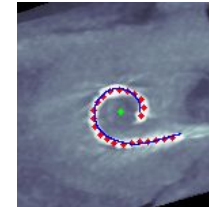
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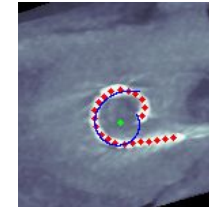
Modified



Nominal



Modified



Nominal

Conclusion

- Pros:
 - Automates much of the manual analysis of CT scans
 - Highly extensible - can be plugged into any data source
 - Tested on a very wide range of CT scans - designed for clinical deployment and real-world application.
 - Accessible - written in Python. All free software, very easy to deploy and run.
 - Orders of magnitude faster (~15 seconds per image). Easy to combine with manual analysis.
- Drawbacks:
 - Cannot be used as standalone tool yet
 - Mathematical spiral models are not ubiquitous - great variation in cochlea shape
- Novel Contributions:
 - Segmentation technique for CI electrode;
 - PCA for direction of the modiolar axis;
 - Pixel Adjacency Graph for shape tracing in images; and
 - Euclidean Distance Residual Minimization for curve fitting in two dimensions.

Future Work

1. Improved optimisation of the cohen spiral fitting
2. More reliable image pre-processing for pixel adjacency graph
1. Runtime numerical validation of segmentation and cochlear view

References

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- [6] Cohen, L., Xu, J., Xu, S., & Clark, G. (1996). Improved and Simplified Methods for Specifying Positions of the Electrode Bands of a Cochlear Implant Array. *The American Journal Of Otology*, 17, 859-865.
- [7] Escudé, B., James, C., Deguine, O., Cochard, N., Eter, E., & Fraysse, B. (2006). The size of the cochlea and predictions of insertion depth angles for cochlear implant electrodes. *Audiology and Neurotology*, 11(Suppl. 1), 27-33.

Appendix

Affine Rotation

- Rotation achieved using affine transformation about the mean
 - Each coordinate (x_a, y_a, z_a) multiplied by $\mathbf{R}$ to give transformed volume, with z axis aligned to modiolar axis
-

PCA Vector.

$$\mathbf{v}_i = \begin{bmatrix} v_{i,x} \\ v_{i,y} \\ v_{i,z} \end{bmatrix}$$

Define new coordinate system.

$$\hat{\mathbf{x}}, \hat{\mathbf{y}}, \hat{\mathbf{z}} = \mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3$$

Affine rotation and shift matrices about the mean, $\mathbf{s}$.

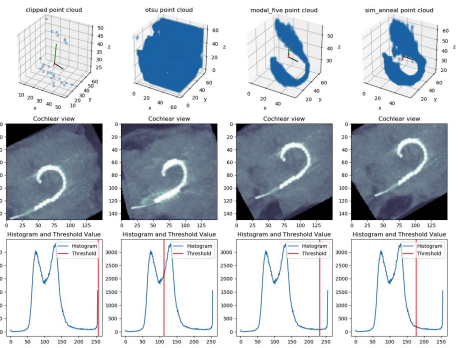
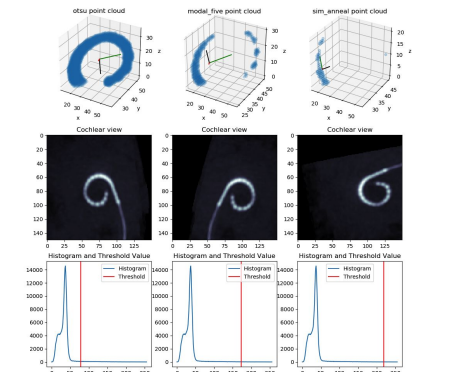
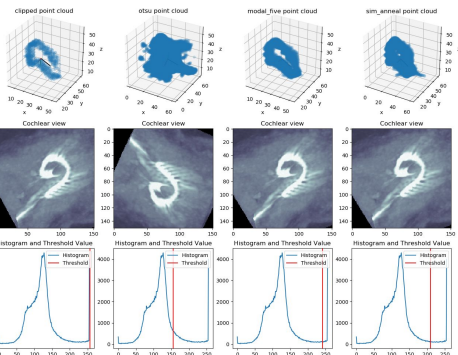
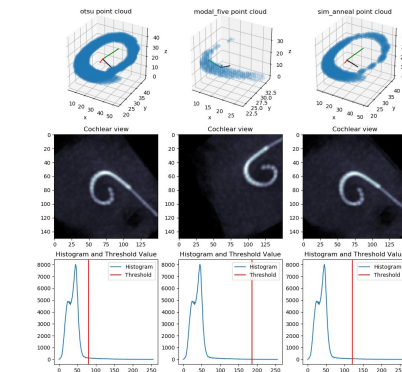
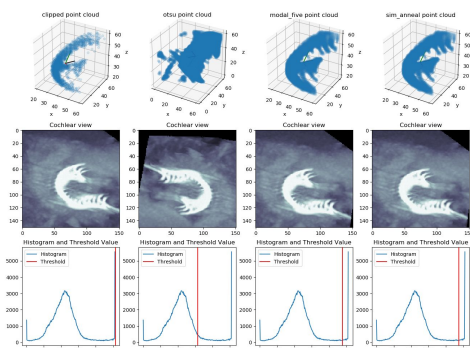
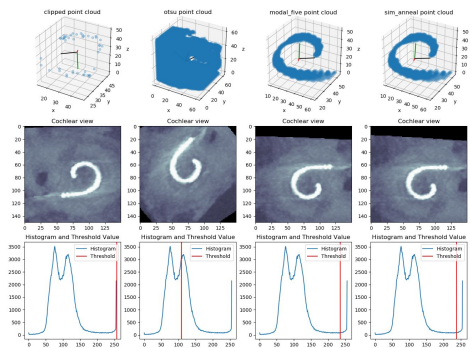
$$\mathbf{R} = \begin{bmatrix} v_{1,x} & v_{2,x} & v_{3,x} & 0 \\ v_{1,y} & v_{2,y} & v_{3,y} & 0 \\ v_{1,z} & v_{2,z} & v_{3,z} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & s_x \\ 0 & 1 & 0 & s_y \\ 0 & 0 & 1 & s_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

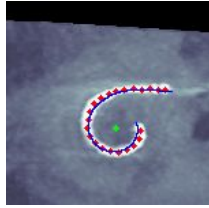
Transform each coordinate.

$$\mathbf{T}\mathbf{R}\mathbf{T}^{-1} \begin{bmatrix} x_a \\ y_a \\ z_a \\ 1 \end{bmatrix} = \begin{bmatrix} \hat{x}_a \\ \hat{y}_a \\ \hat{z}_a \\ 1 \end{bmatrix}$$

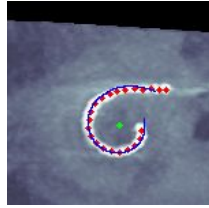
Cochlear Views



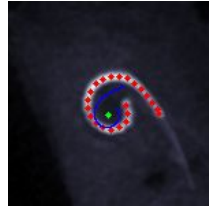
Electrodes and Modiolus



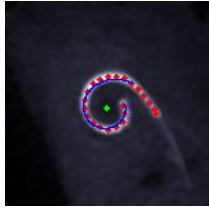
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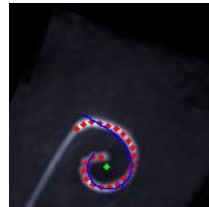
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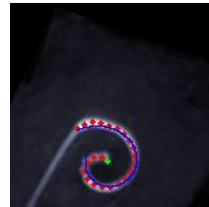
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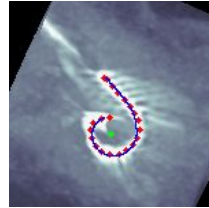
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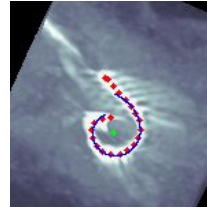
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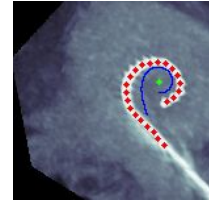
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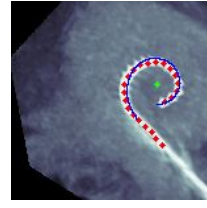
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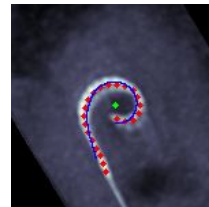
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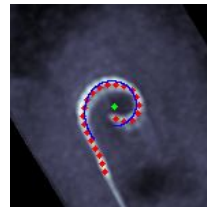
Modified



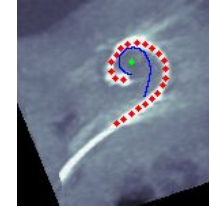
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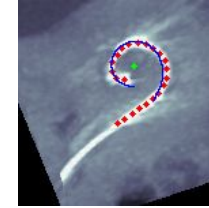
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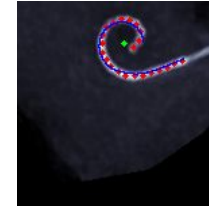
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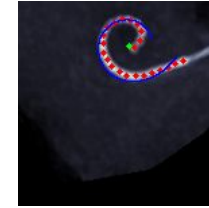
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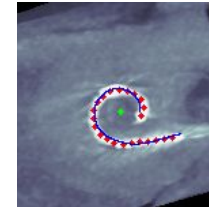
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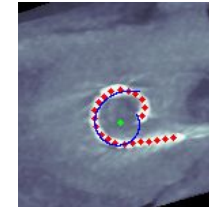
Modified



Nominal



Modified



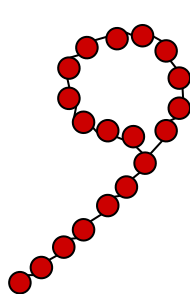
Nominal

Broken Electrode Paths

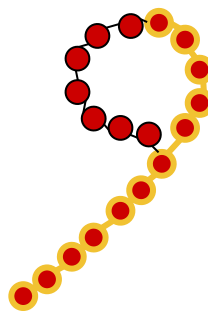
- Errors in preprocessing create a bridge between spiral and the lead wire



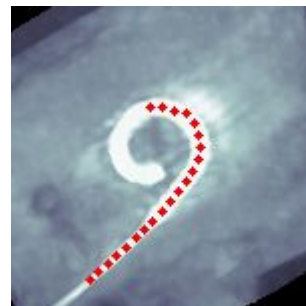
Dilation and blurring
merge regions



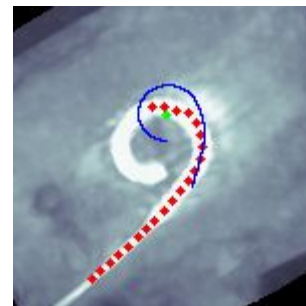
Bridge forms
between spiral and
lead wire



Electrode path
incorrectly found



Incorrect electrode
positions



Bad Cohen Spiral fit

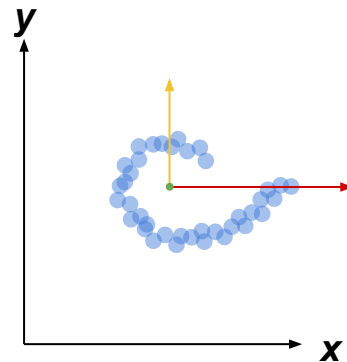
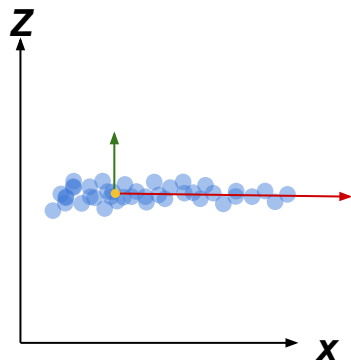
Rotation

Define Affine Rotation

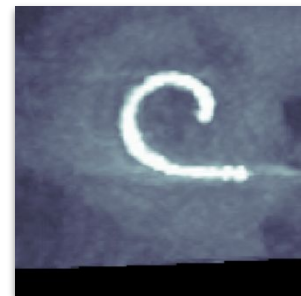
PCA Vector: $\mathbf{v}_i = \begin{bmatrix} v_{i,x} \\ v_{i,y} \\ v_{i,z} \end{bmatrix}$

$$\mathbf{R} = \begin{bmatrix} v_{1,x} & v_{2,x} & v_{3,x} & 0 \\ v_{1,y} & v_{2,y} & v_{3,y} & 0 \\ v_{1,z} & v_{2,z} & v_{3,z} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Align Coordinate Axes

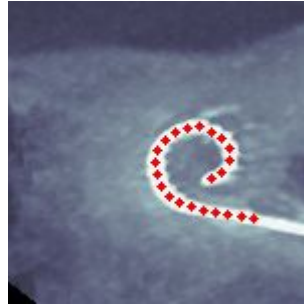


Attain Cochlear View

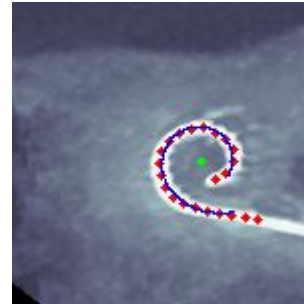


Results - Good Fits

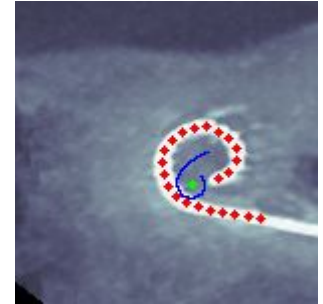
Electrode Path



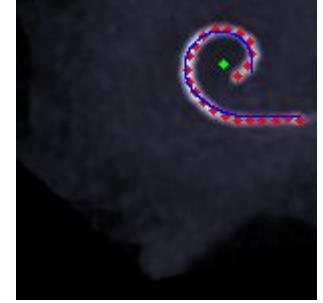
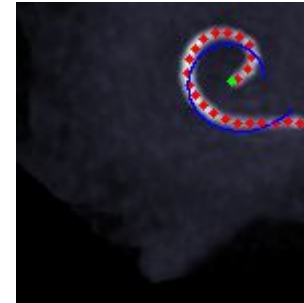
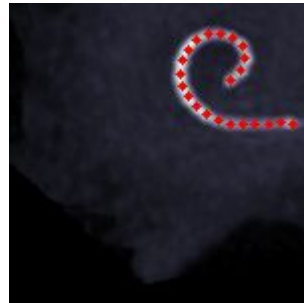
Nominal



Modified



***Nominal Spiral is a
Better Fit***



***Modified Spiral is a
Better Fit***