Chest EIT: why it's difficult, and what we're doing about it?

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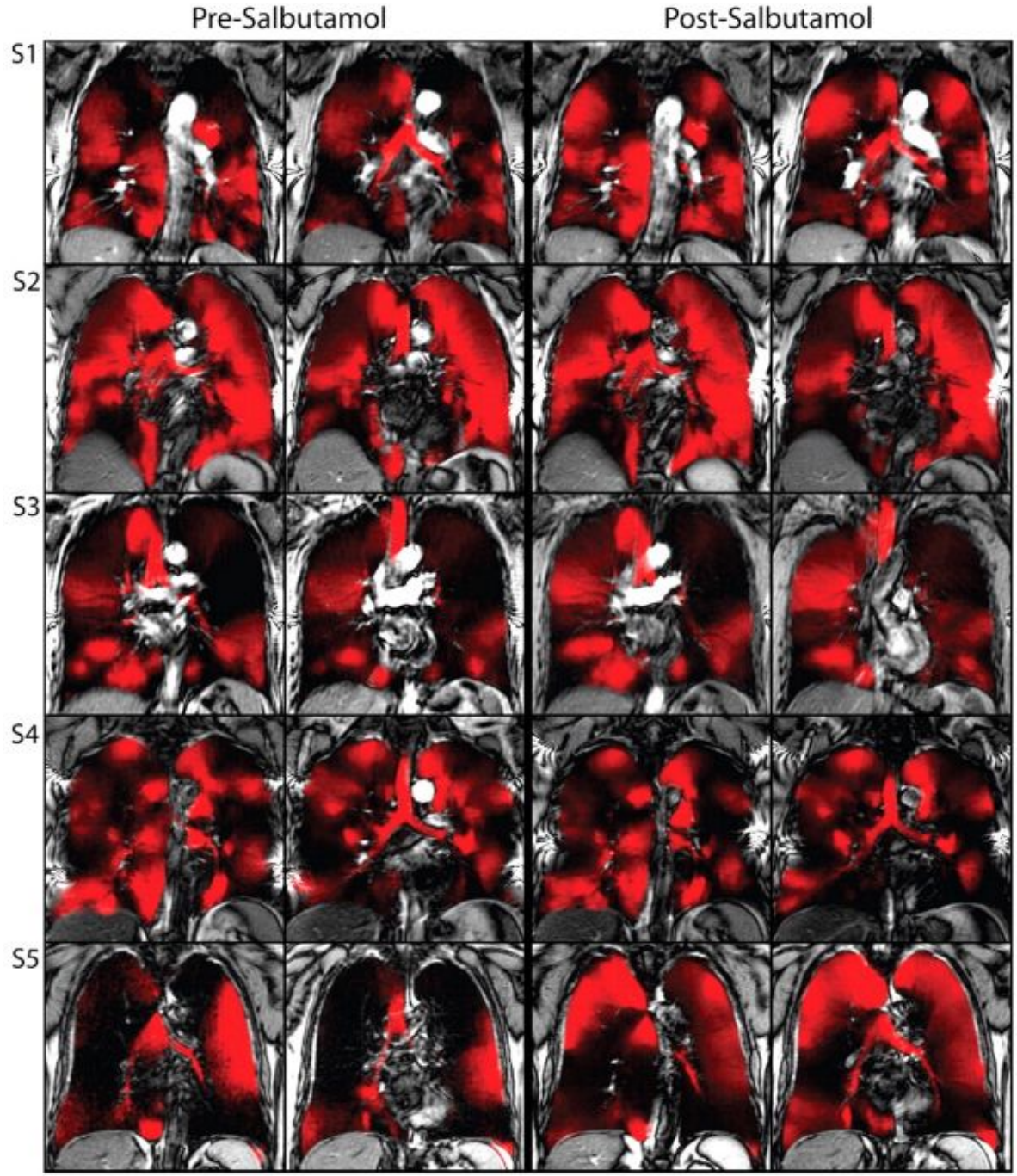
Lung Imaging

Lung Imaging

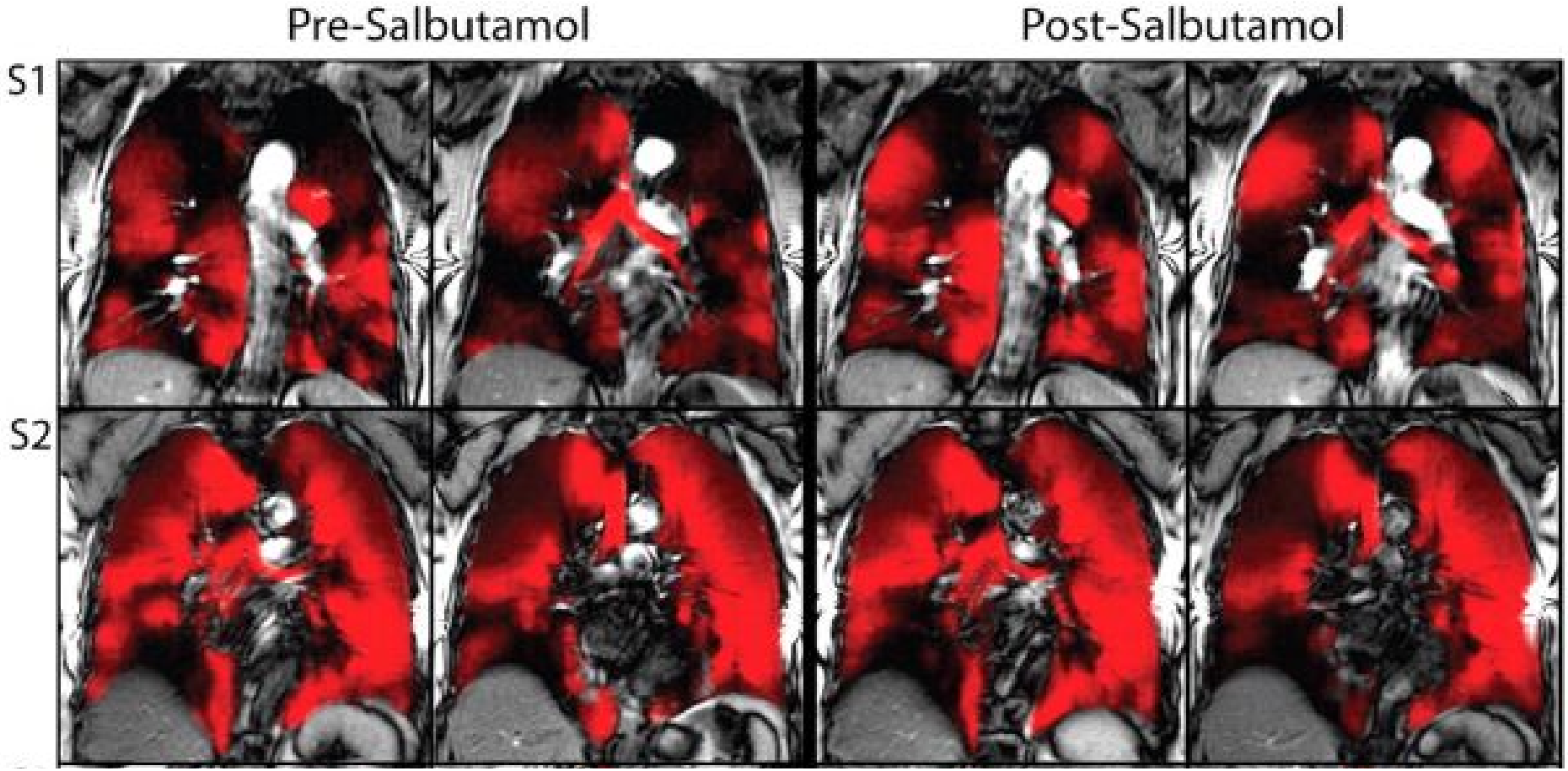
Source: Kirby et al, Radiology 261.1 (2011)

Pre- and post-salbutamol ^{3}He MR images (red) registered to two center coronal thoracic ^{1}H MR images (gray scale) for five representative patients with COPD

S1, S2: stage II disease,
S3, S4: stage III disease,
S5: stage IV disease.



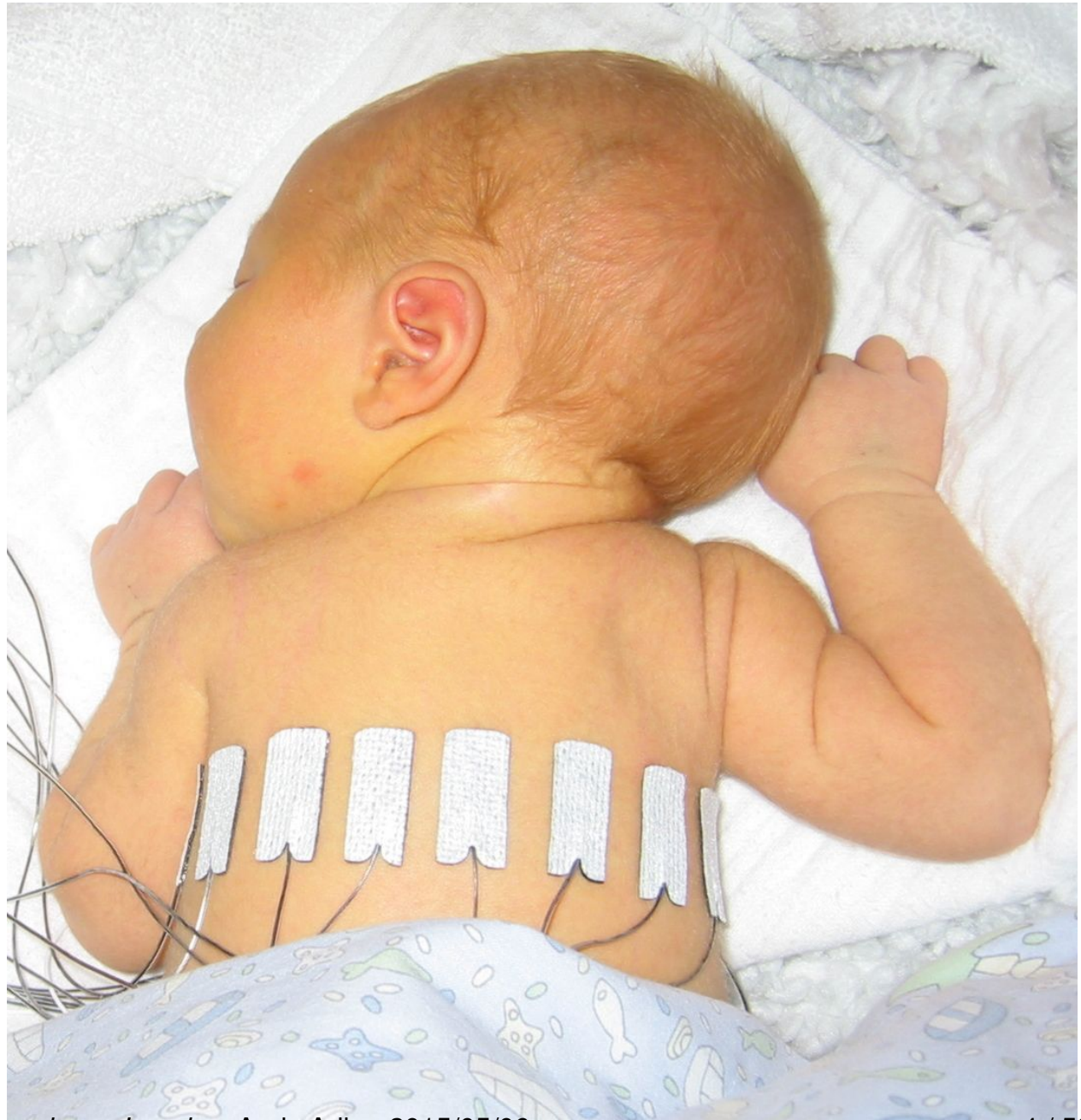
Imaging $\Rightarrow$ new clinical insights



Electrical Impedance Tomography

Electrical Impedance Tomography

10-day old healthy baby with EIT electrodes



Source: Heinrich, Schiffmann, Frerichs, Klockgether-Radke, Frerichs; *Intensive Care Med*; 2006. eidors3d.sf.net/data_contrib/if-neonate-spontaneous

EIT – Purpose?

EIT – Purpose?

- Imaging –-

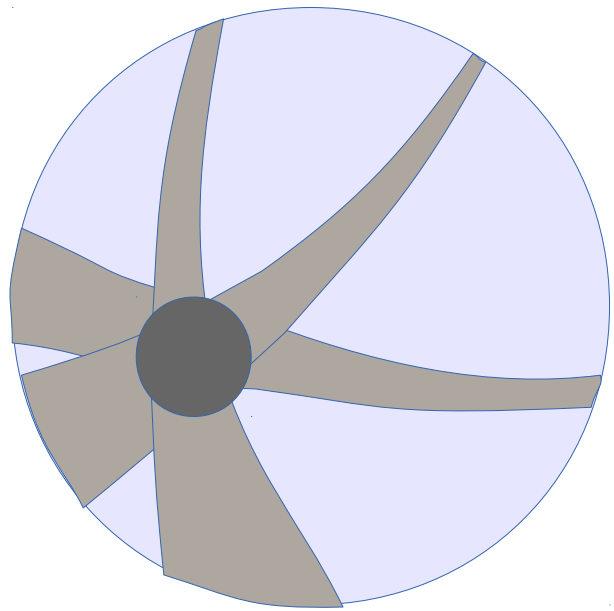
EIT – Purpose?

- Imaging −−
- Monitoring ++

EIT – easy?

- Audio-frequency analog circuits
- Low frequency A/D converters
- mV-range voltage measurement

- Simple imaging algorithms?



EIT – ~~easy~~!

Why is EIT difficult?

Inverse Problems . . . *Plato's cave*

Plato's cave . . . Shadows on the wall

Source: iamcriselleeee.files.wordpress.com/2013/11/cave-2.jpg

Inverse Problems

Forward Problem: $\textit{Forms} \Rightarrow \textit{Shadows}$

Inverse Problems

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- Ill-conditioned
  Sensitivity to some movements is low

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- Ill-conditioned
  Sensitivity to some movements is low
- Ill-posed
  Some movements don't change shadows
- Noisy
  Flickering light

Inverse Problems: EIT

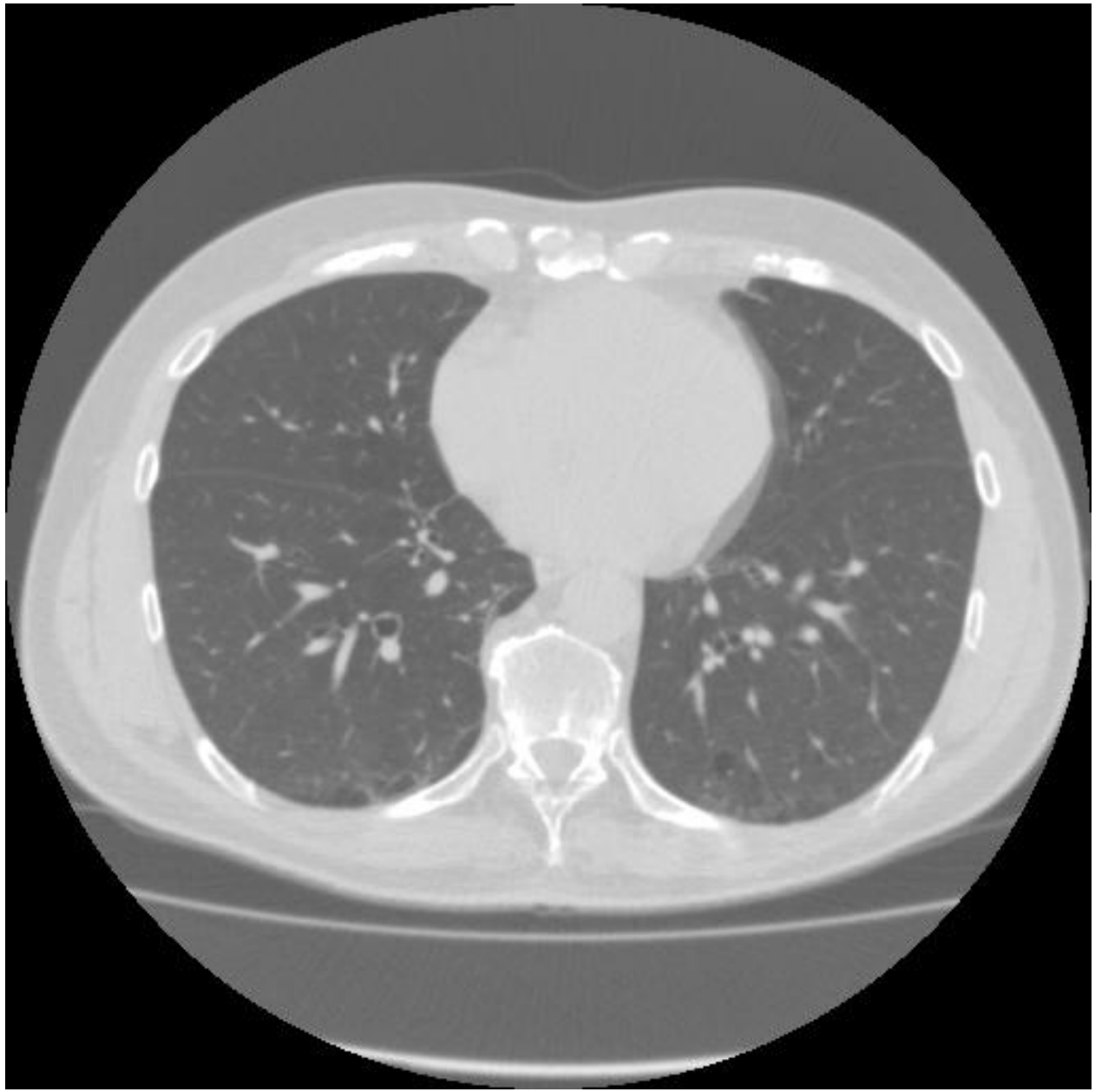
Ill-conditioned

- Low sensitivity to phenomena of interest
- High sensitivity to phenomena *not* of interest

Ill-conditioned . . .

Healthy Adult
Male CT slide

Source:
eidors3d.sf.net/tutorial/
netgen/extrusion



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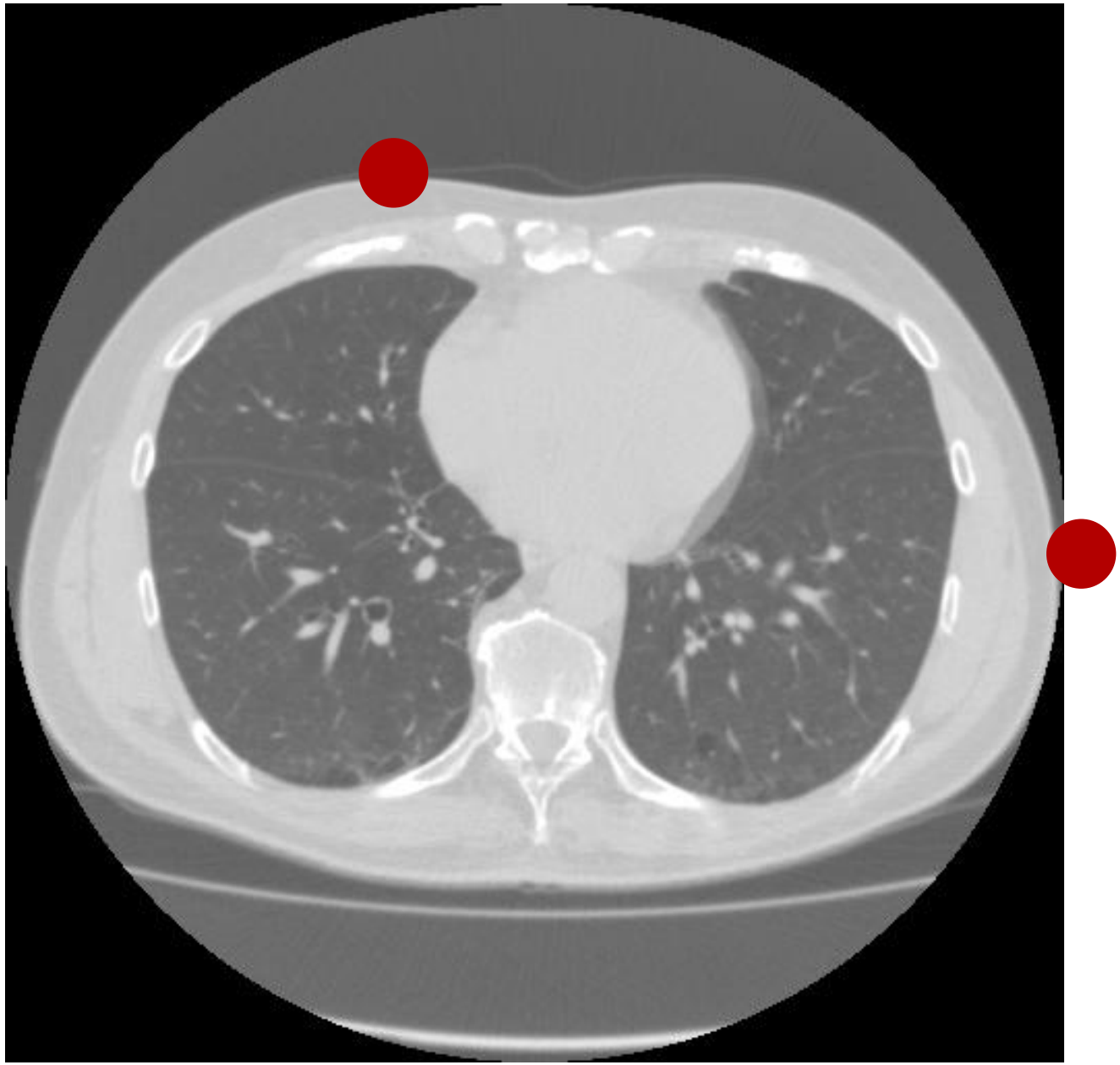

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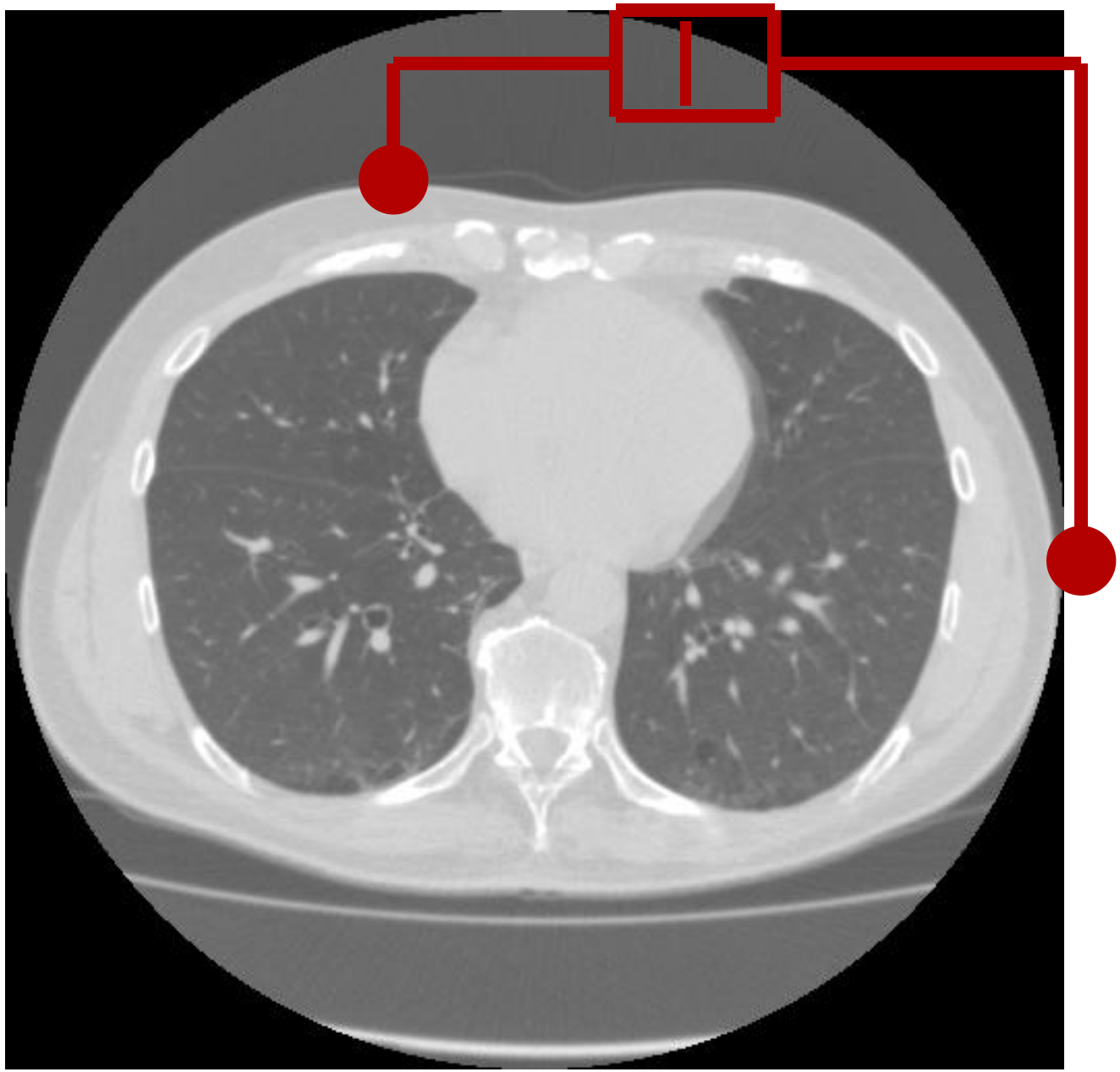

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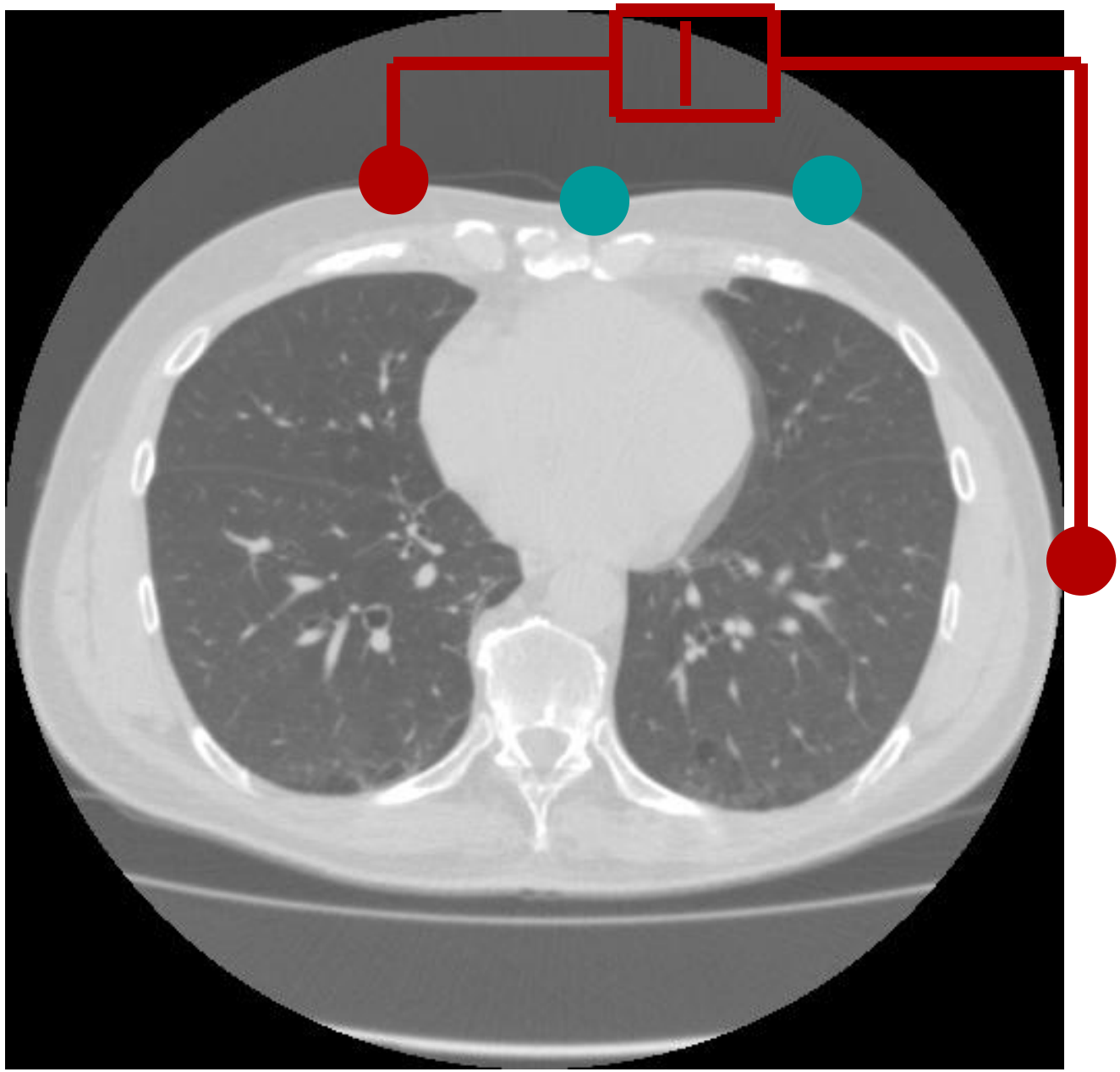

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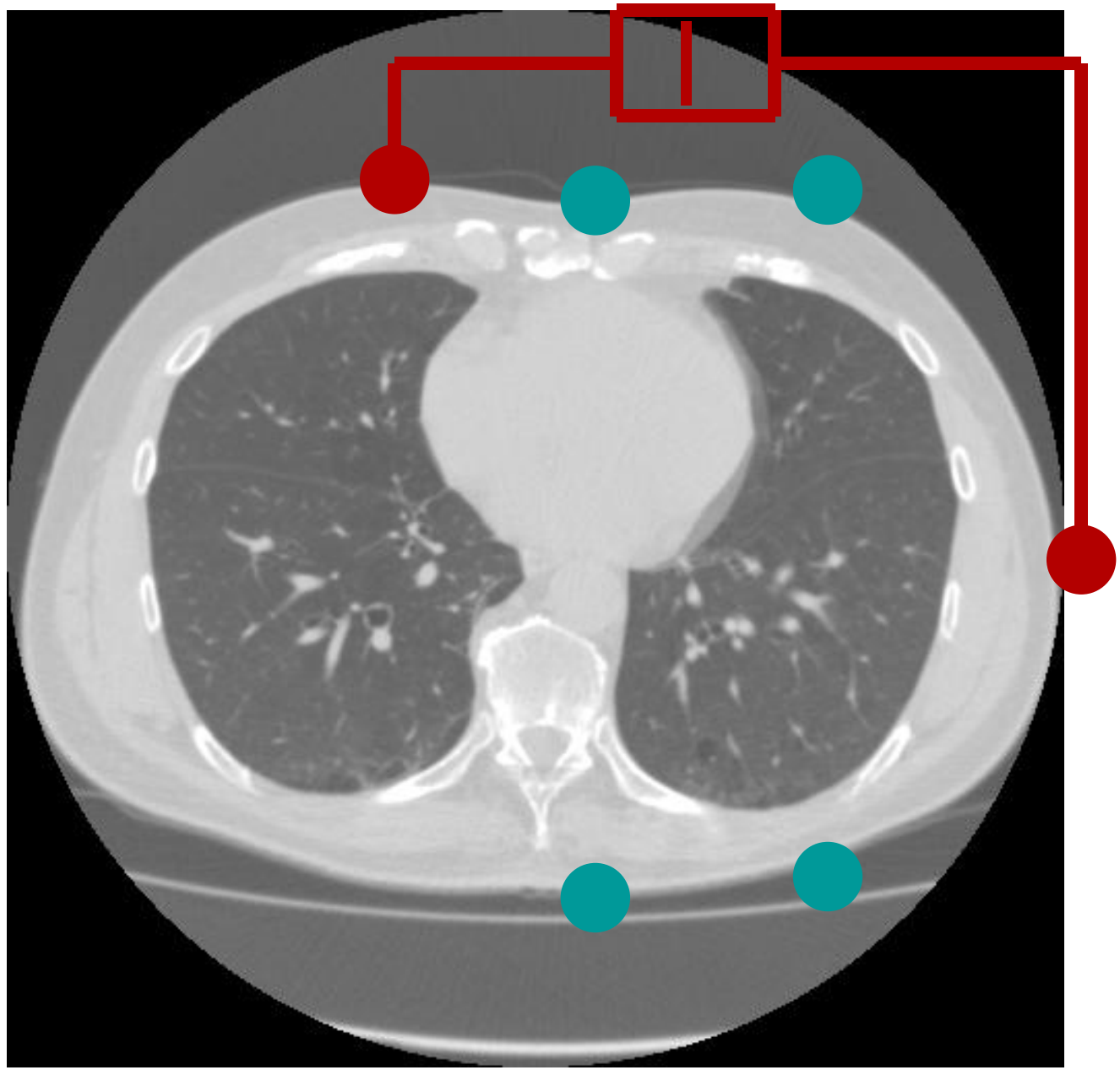
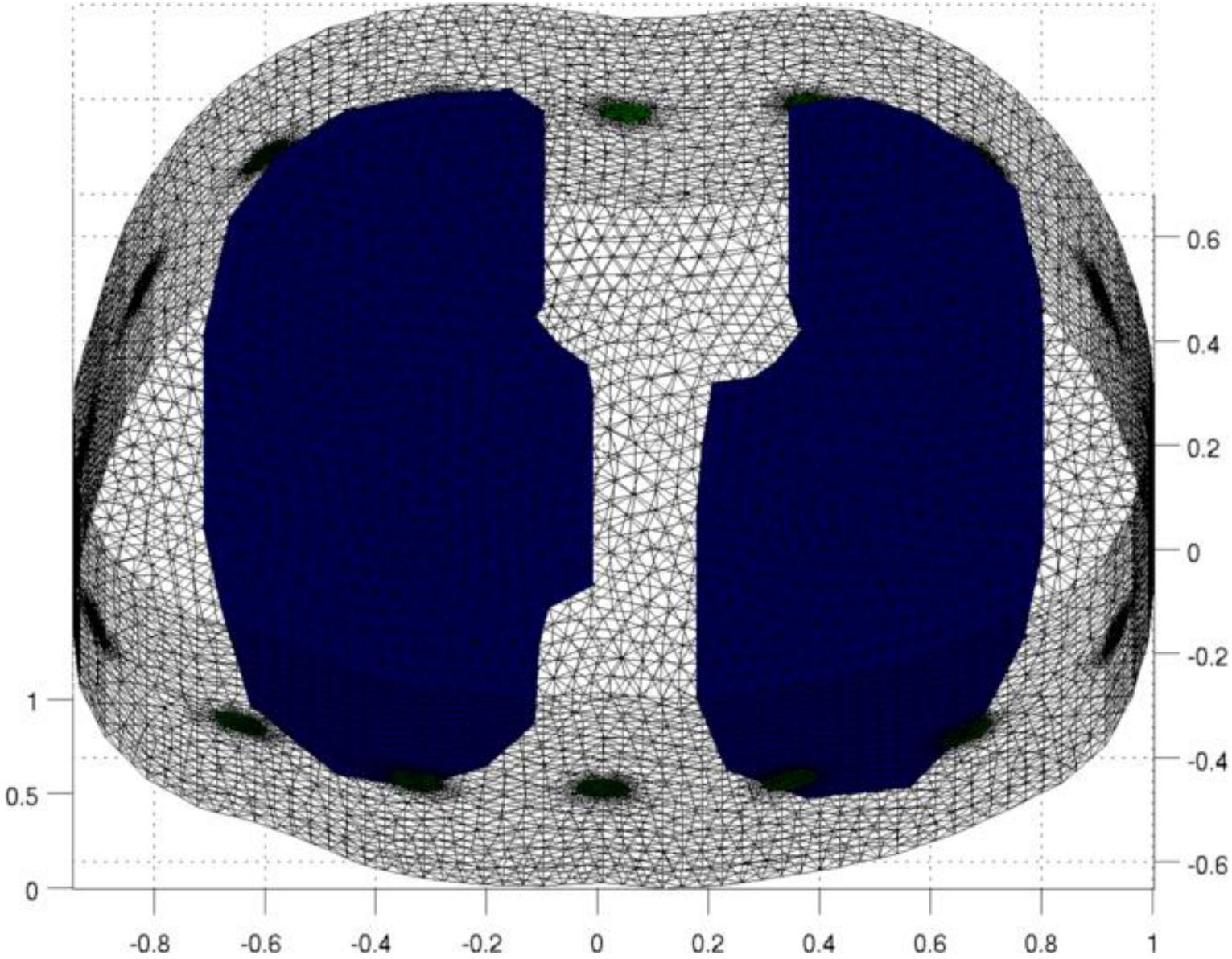


Finite Element Modelling

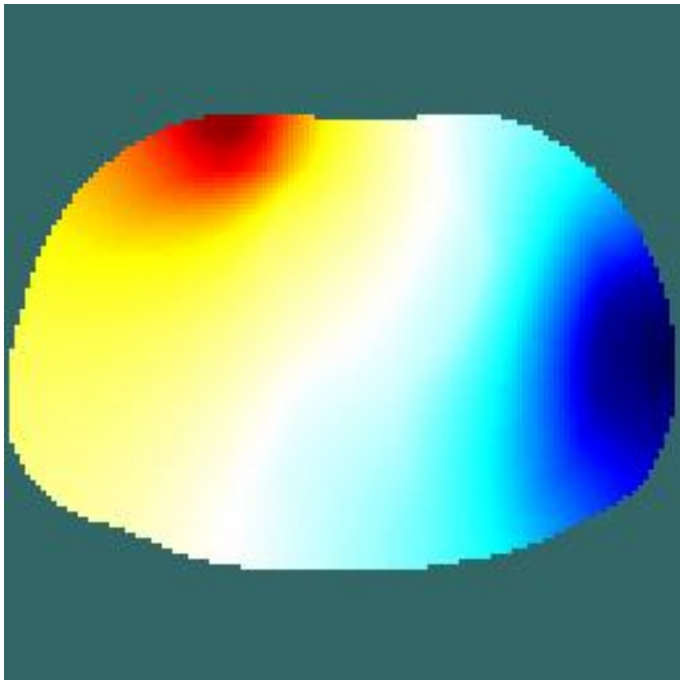


Finite Element Modelling

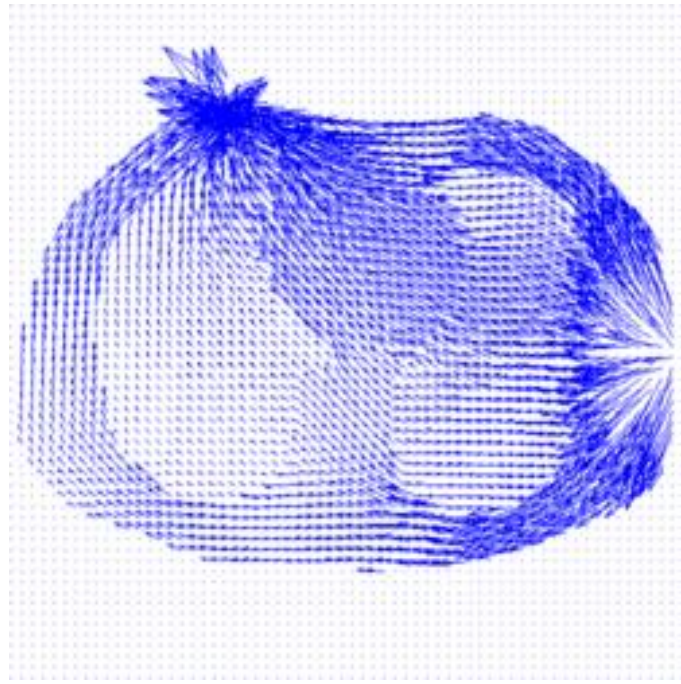
Step 1: Create Finite Element Model

```
%%%% THORAXMDL01
% get contours
thorax = shape_library('get','adult_male','boundary');
rlung  = shape_library('get','adult_male','right_lung');
llung  = shape_library('get','adult_male','left_lung');
% one could also run:
% shape_library('get','adult_male');
% to get all the info at once in a struct

% show the library image
shape_library('show','adult_male');
print_convert thoraxmdl01a.jpg '-density 100'
%%%% THORAXMDL02
shape = { 1,                      % height
          {thorax, rlung, llung}, % contours
          [4,50],                 % perform smoothing with 50 points
          0.04};                  % small maxh (fine mesh)

elec_pos = [ 16,                  % number of elecs per plane
             1,                   % equidistant spacing
             0.5]';               % a single z-plane

elec_shape = [0.05,               % radius
              0,                  % circular electrode
              0.01 ]';             % maxh (electrode refinement)

fmdl = ng_mk_extruded_model(shape, elec_pos, elec_shape);
% this similar model is also available as:
% fmdl = mk_library_model('adult_male_16el_lungs');

[stim,meas_sel] = mk_stim_patterns(16,1,[0,1],[0,1],{'no_meas_current'}, 1);
fmdl.stimulation = stim;

img=mk_image(fmdl,1);
img.elem_data(fmdl.mat_idx{2})= 0.3; % rlung
img.elem_data(fmdl.mat_idx{3})= 0.3; % llung

clf; show_fem(img); view(0,70);
print_convert thoraxmdl02a.jpg '-density 100'
```

Finite Element Modelling



Simulated Voltages



Voxel Currents

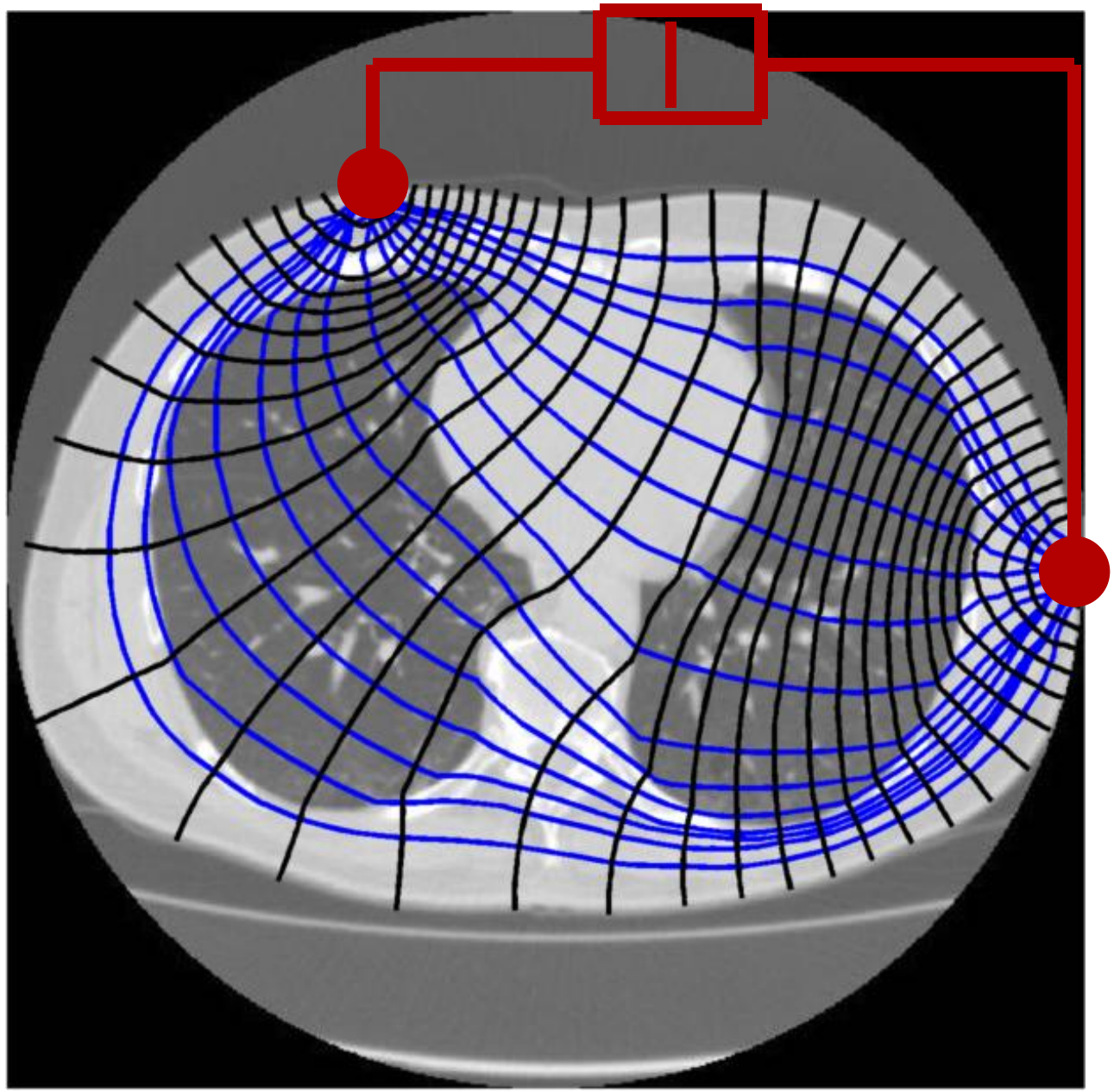
Finite Element Modelling

Step 2: Forward solve and current streamlines

```
img_v = rmfield(img, 'elem_data');
img_v.node_data = vh.volt(:,1);
img_v.calc_colours.npoints = 128;

PLANE= [inf,inf,0.35]; % show voltages on this slice

subplot(221);
show_slices(img_v,PLANE); axis off; axis equal
print_convert thoraxmdl03a.jpg
%
%%%% THORAXMDL04
img_v = img;
img_v.fwd_model.mdl_slice_mapper.npx = 64;
img_v.fwd_model.mdl_slice_mapper.npy = 64;
img_v.fwd_model.mdl_slice_mapper.level = PLANE;
q = show_current(img_v, vh.volt(:,1));
quiver(q.xp,q.yp, q.xc,q.yc,10,'b');
axis tight; axis image; ylim([-1 1]);axis off
print_convert thoraxmdl04a.jpg

%%%% THORAXMDL05
img_v.fwd_model.mdl_slice_mapper.npx = 1000;
img_v.fwd_model.mdl_slice_mapper.npy = 1000;
img_v.fwd_model.mdl_slice_mapper.level = PLANE;

% Calculate at high resolution
q = show_current(img_v, vh.volt(:,1));

pic = shape_library('get','adult_male','pic');
imagesc(pic.X, pic.Y, pic.img);
% imgt= flipdim(imread('thorax-mdl.jpg'),1); imagesc(imgt);
colormap(gray(256)); set(gca,'YDir','normal');
hold on

sx = linspace(-.5,.5,15)';
sy = 0.05 + linspace(-.5,.5,15)';
hh=streamline(q.xp,q.yp, q.xc, q.yc,sx,sy); set(hh,'Linewidth',2, 'color','b');
hh=streamline(q.xp,q.yp,-q.xc,-q.yc,sx,sy); set(hh,'Linewidth',2, 'color','b');

axis equal; axis tight; axis off; print_convert thoraxmdl05a.jpg
```

Thorax Propagation

CT Slice with simulated current streamlines and voltage equipotentials



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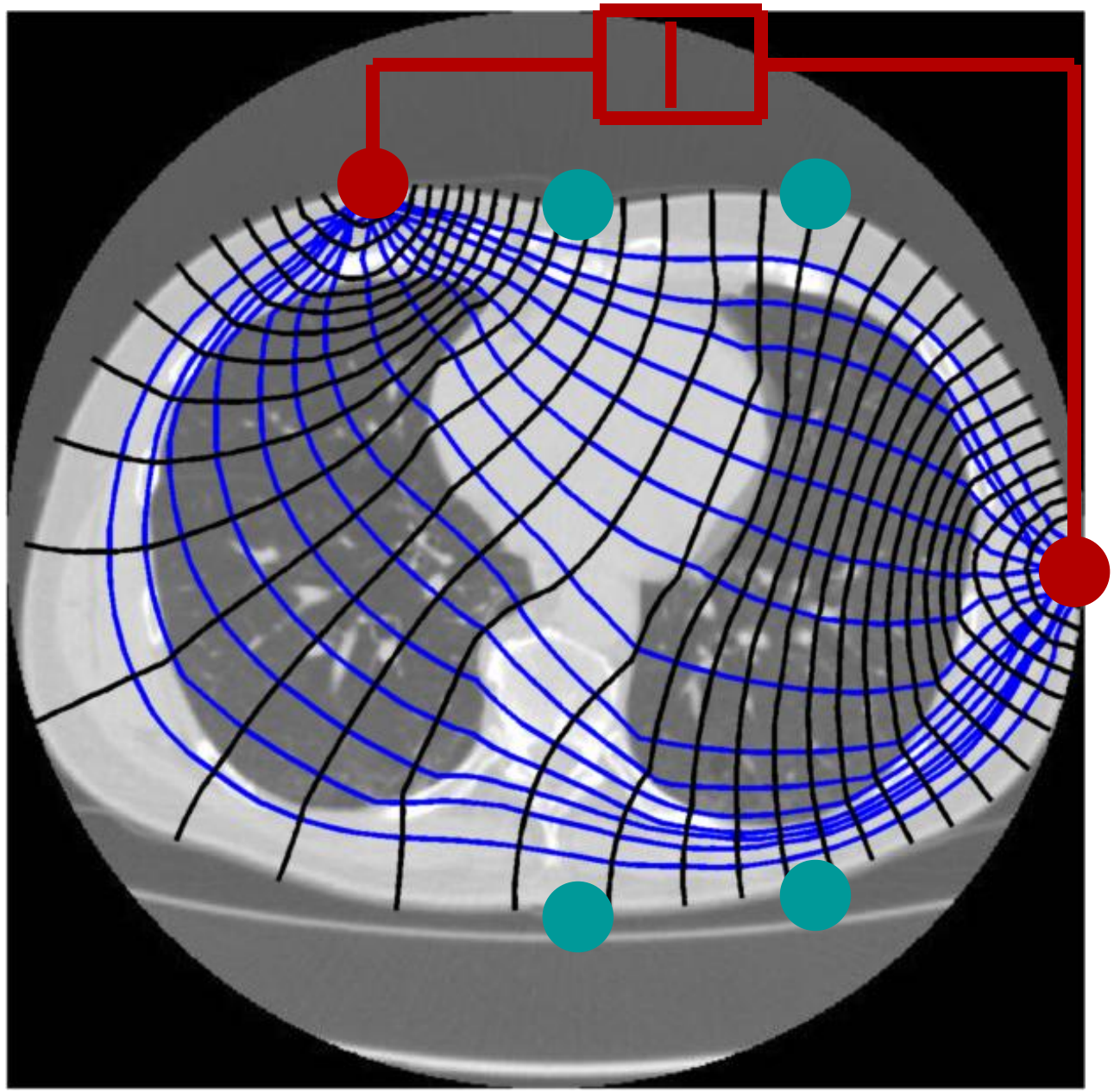
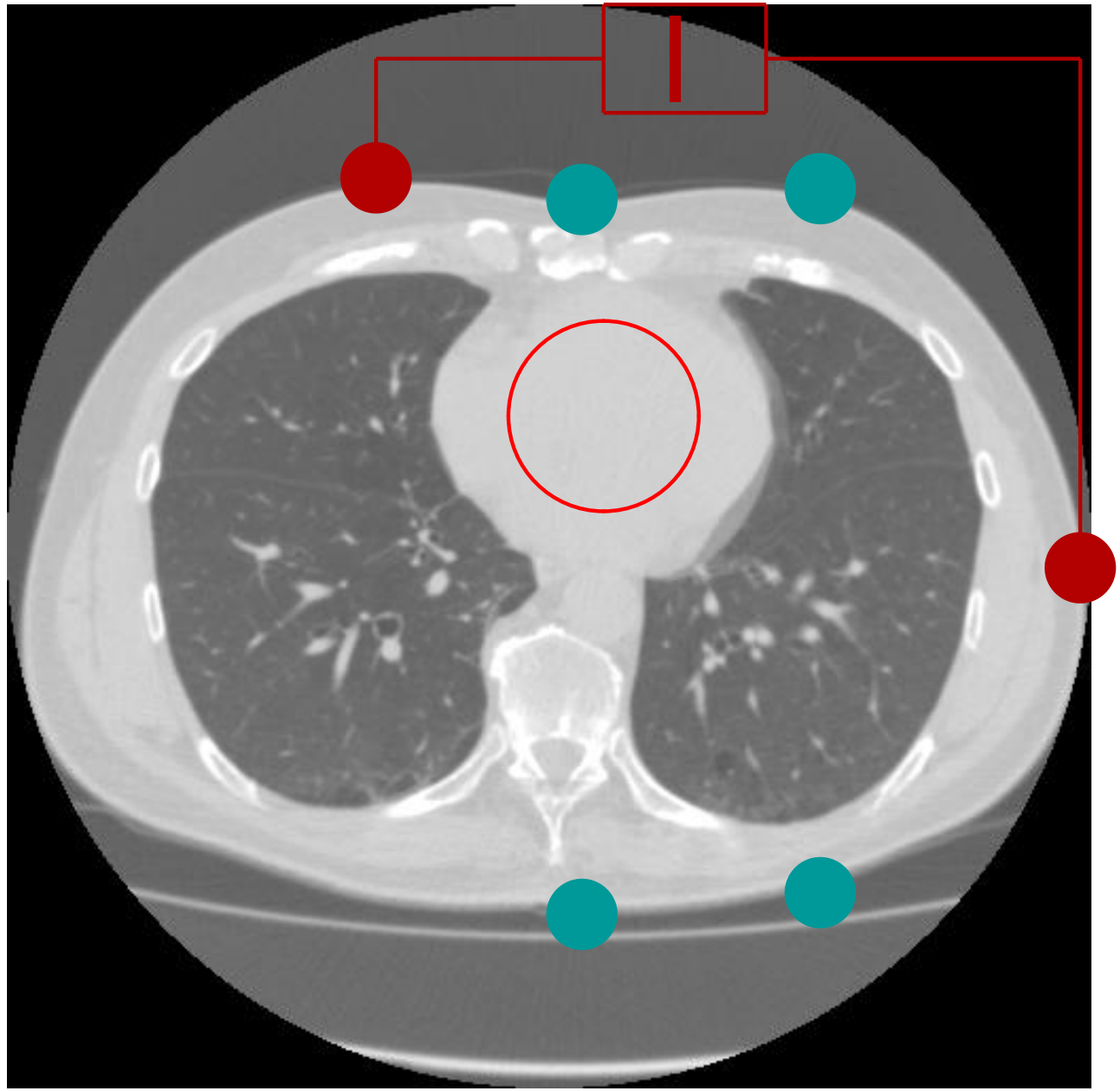


Changing Conductivity

Heart receives blood (diastole) and is more conductive



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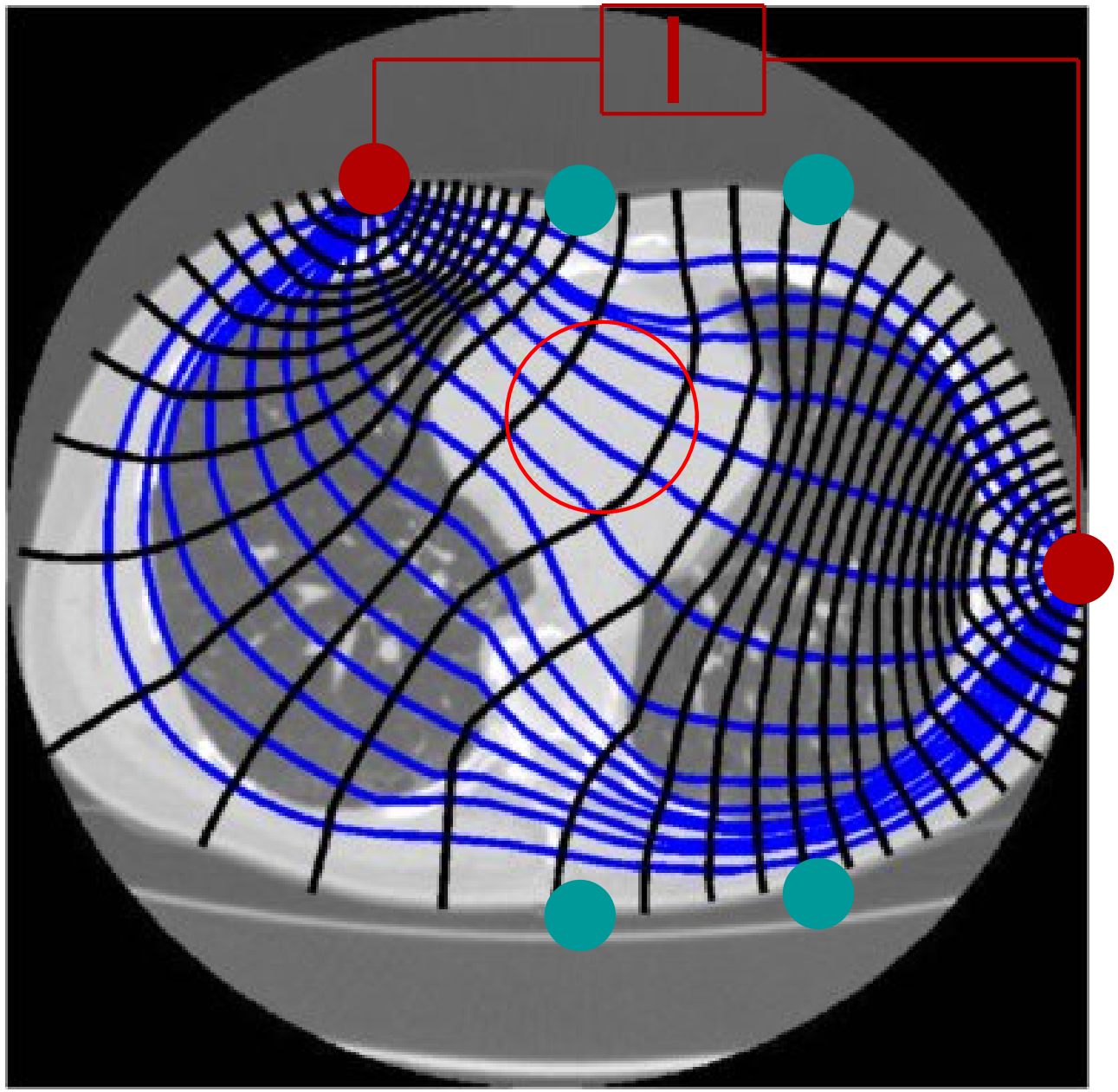
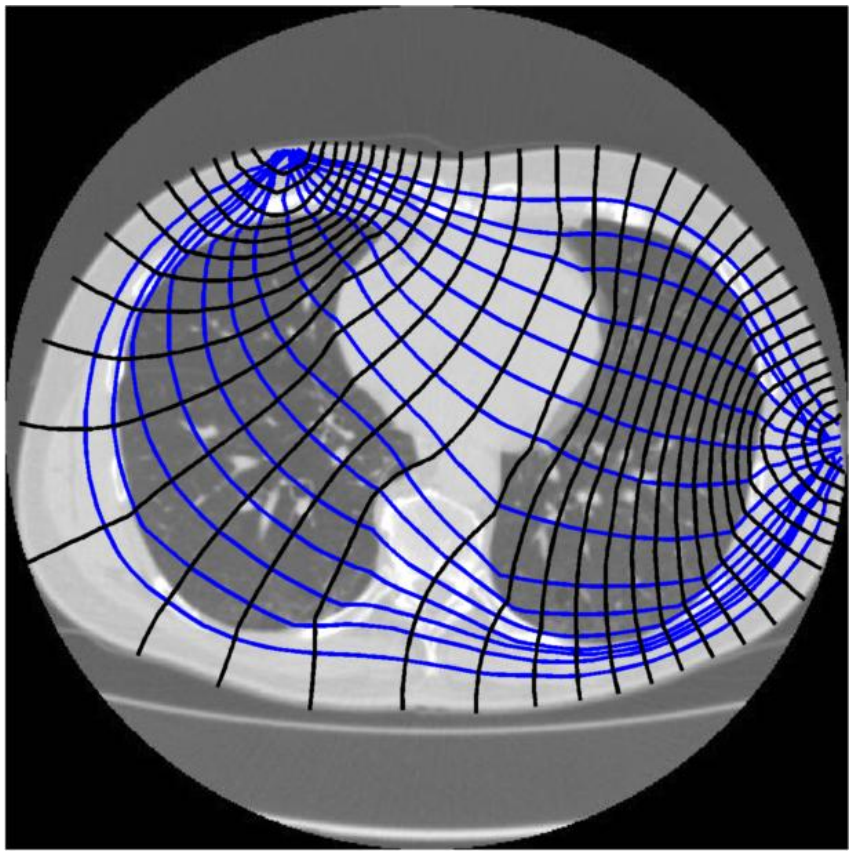
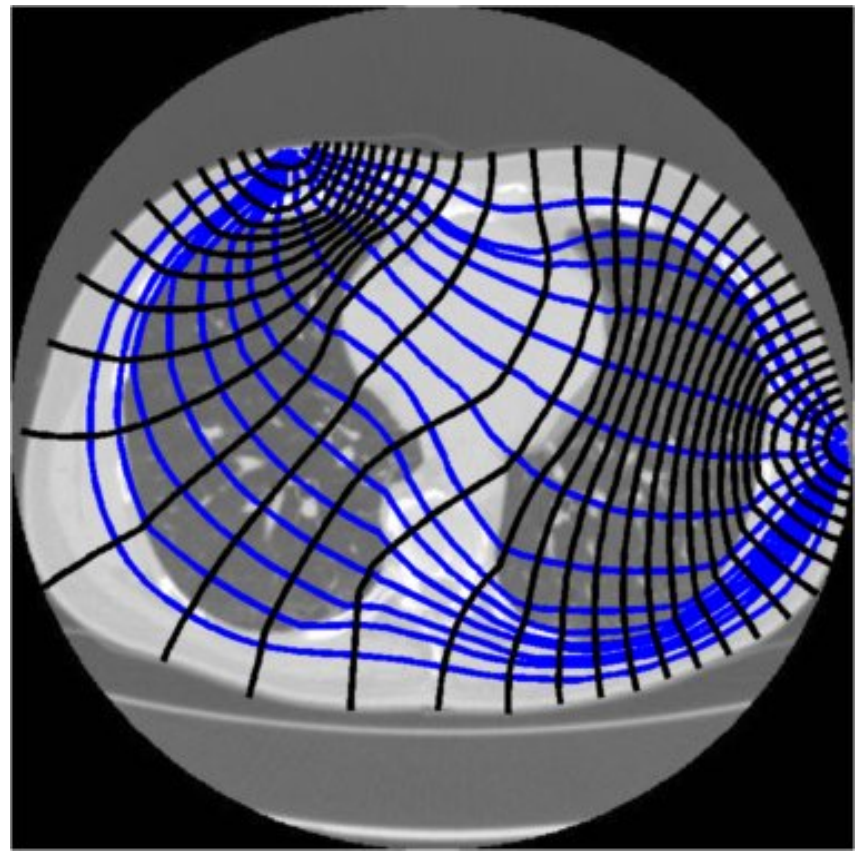


Ill-conditioned: low sensitivity





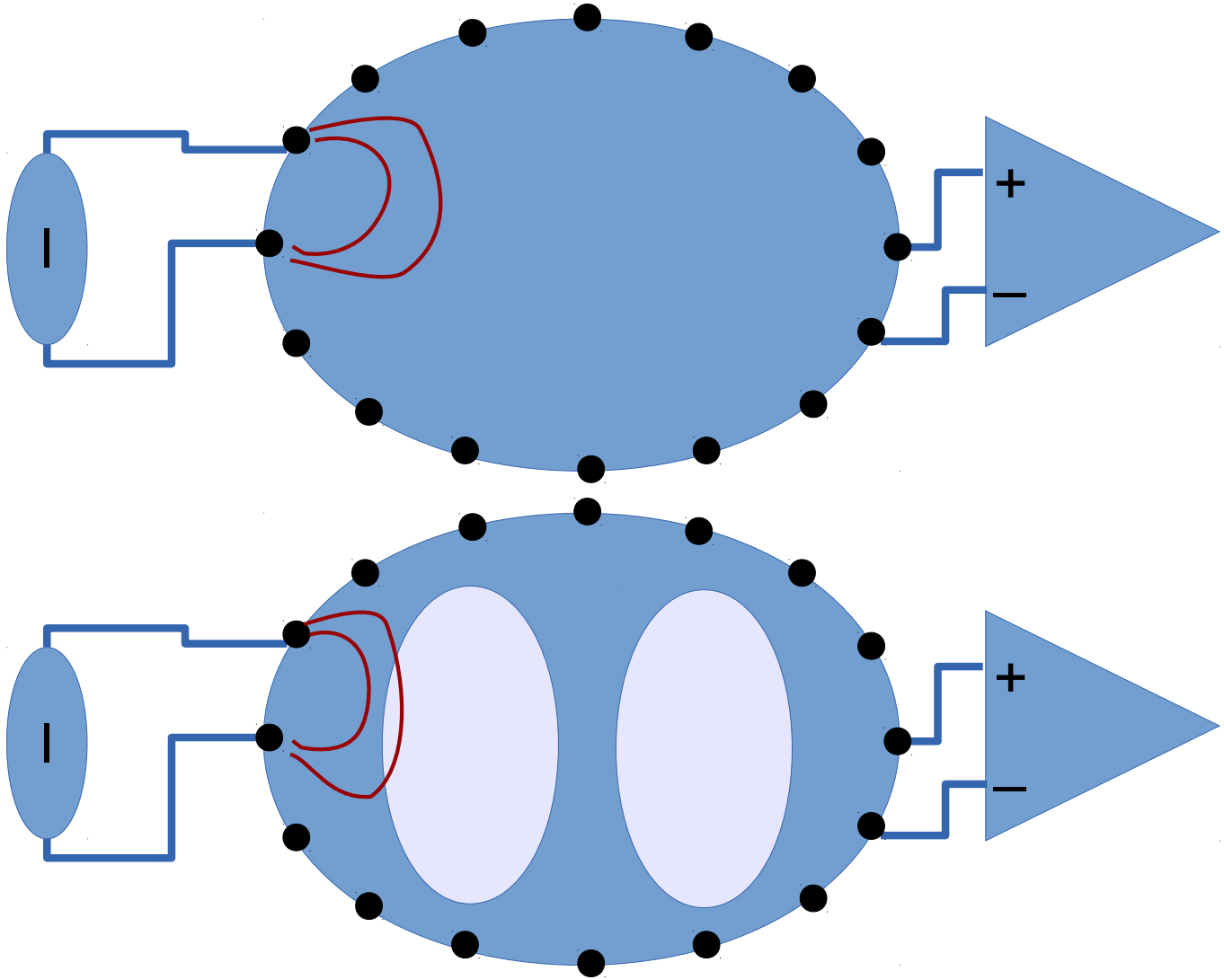
Finite Element Modelling

Step 3: Change conductivity and re-solve

```
    select_fcn = inline('(x-0.1).^2+(y-0.3).^2<0.2^2','x','y','z');
    memb_frac = elem_select( img.fwd_model, select_fcn);
img=mk_image(fmdl,1);
    img.elem_data = 1 + memb_frac*2.0;
img.elem_data(fmdl.mat_idx{2})= 0.3; % rlung
img.elem_data(fmdl.mat_idx{3})= 0.3; % llung
    show_fem(img)
img_v = img;
% Stimulate between elecs 16 and 5 to get more interesting pattern
img_v.fwd_model.stimulation(1).stim_pattern = sparse([16;5],1,[1,-1],16,1);
img_v.fwd_solve.get_all_meas = 1;
vh = fwd_solve(img_v);

img_v = rmfield(img, 'elem_data');
img_v.node_data = vh.volt(:,1);
img_v.calc_colours.npoints = 128;

PLANE= [inf,inf,0.35]; % show voltages on this slice
```

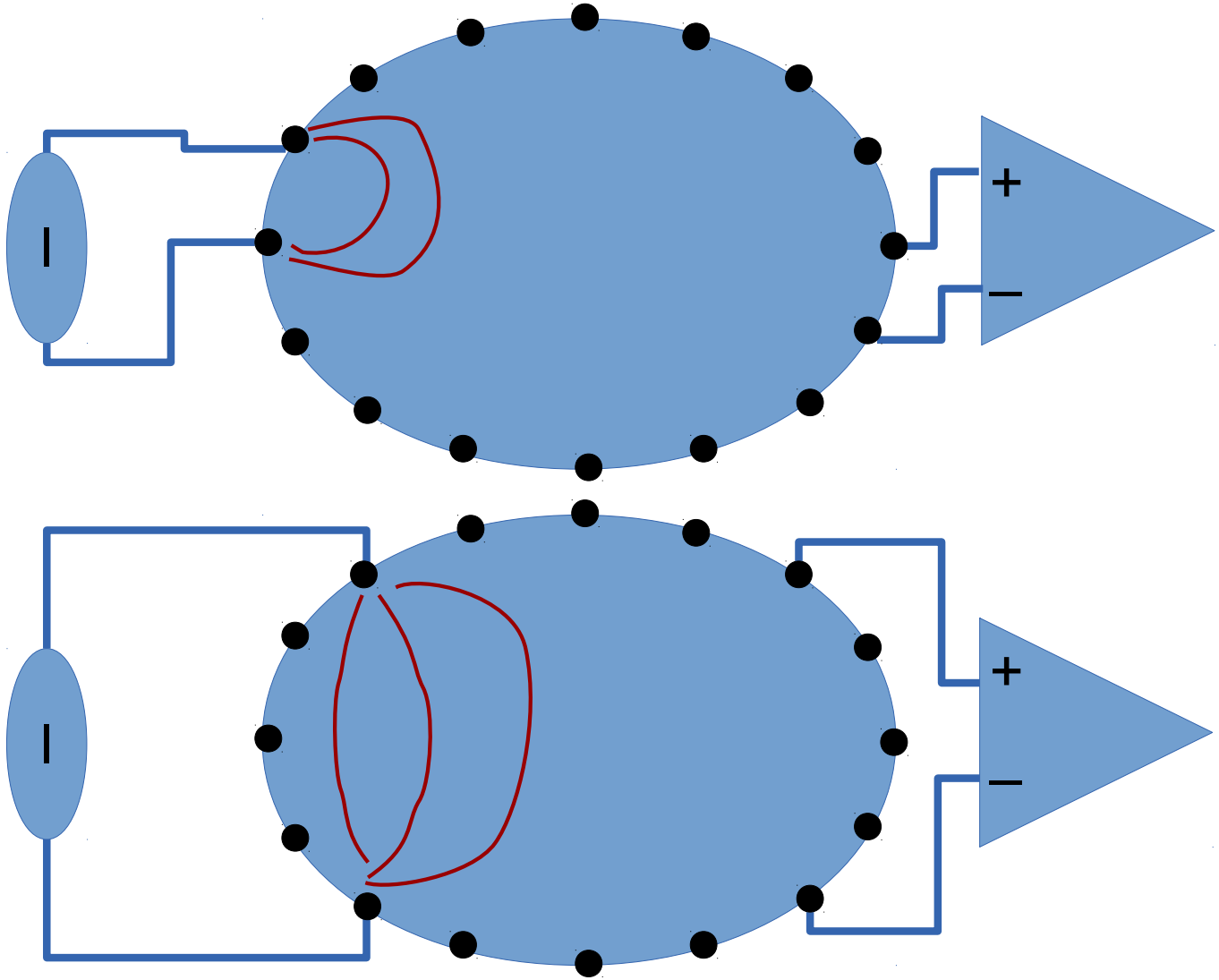
```
clf
imagesc(pic.X, pic.Y, pic.img); colormap(gray(256)); set(gca,'YDir','normal');
hh=streamline(q.xp,q.yp, q.xc, q.yc,sx,sy); set(hh,'Linewidth',2);
hh=streamline(q.xp,q.yp,-q.xc,-q.yc,sx,sy); set(hh,'Linewidth',2);

[x y] = meshgrid( linspace(pic.X(1), pic.X(2),size(imgs,1)), ...
                  linspace(pic.Y(2), pic.Y(1),size(imgs,2)));
hold on;
contour(x,y,imgs,31);
hh= findobj('Type','patch'); set(hh,'LineWidth',2)

hold off; axis off; axis equal; %ylim([50,450]);
print_convert thoraxmdl07a.jpg
```

Non-conductive lungs decrease sensitivity



Relative sensitivity = 2.8×

Own goal: adjacent stimulation and measurement



Relative sensitivity = 20.6×

Finite Element Modelling

CODE: Adjacent vs. Skip 4

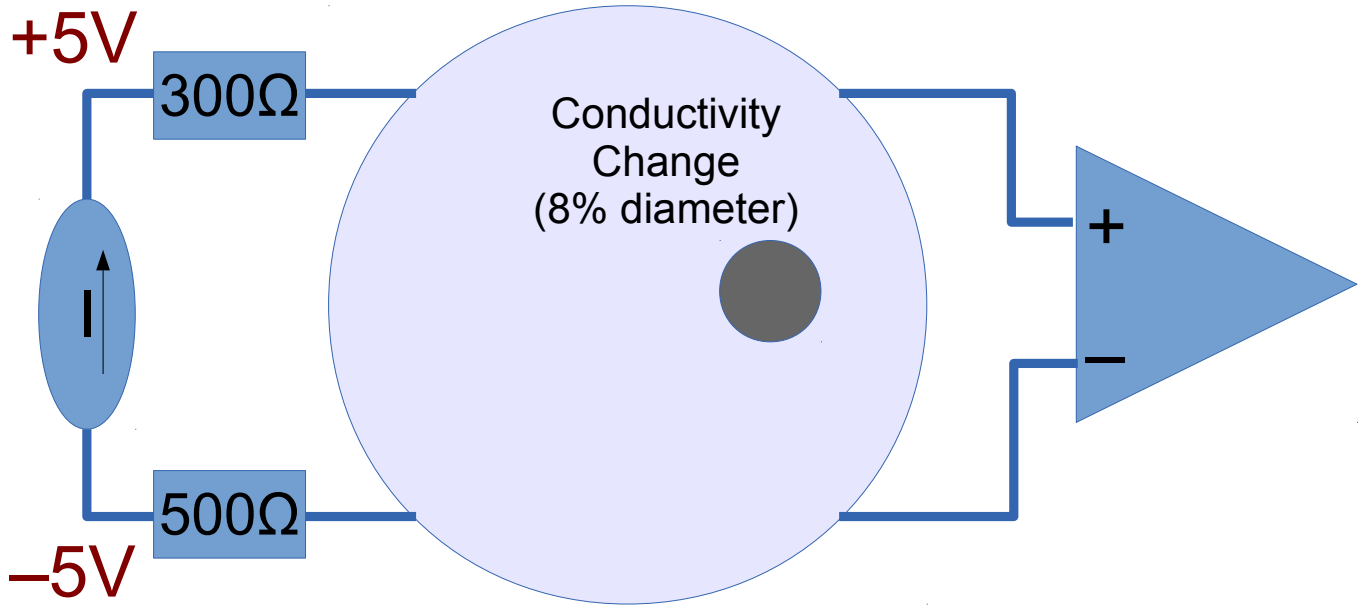
```
extra={'ball','solid ball = sphere(0,0,1;0.1);'}
fmdl= ng_mk_cyl_models(2,[16,1],[.05],extra);
fmdl.stimulation = mk_stim_patterns(16,1,[0,1],[0,1],{},1);
img= mk_image(fmdl,1);                vh = fwd_solve(img);
img.elem_data(fmdl.mat_idx{2}) = 2;   vi = fwd_solve(img);
s1 = norm(vh.meas - vi.meas);

fmdl.stimulation = mk_stim_patterns(16,1,[0,5],[0,5],{},1);
img= mk_image(fmdl,1);                vh = fwd_solve(img);
img.elem_data(fmdl.mat_idx{2}) = 2;   vi = fwd_solve(img);
s2 = norm(vh.meas - vi.meas);

disp(s2/s1)
```

Inverse Problems: EIT

Ill-conditioned

- Low sensitivity to phenomena of interest
- High sensitivity to phenomena *not* of interest

EIT Instrumentation



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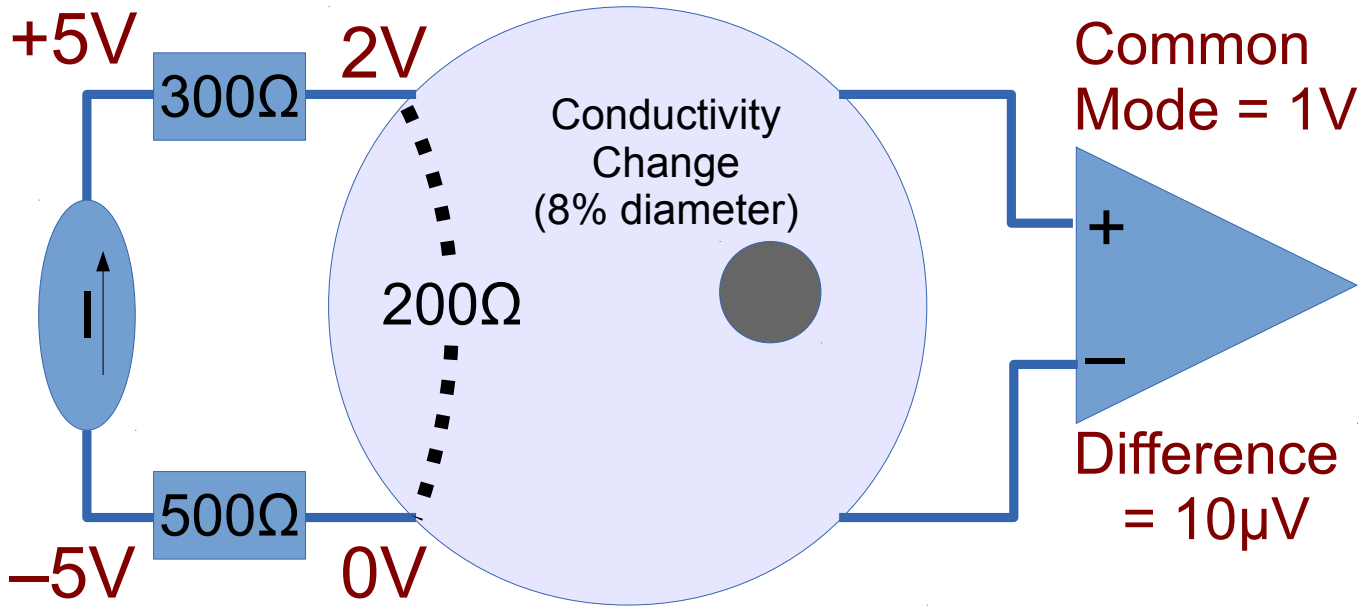

Amplifier Requirements

- Common Mode Rejection Ratio (CMRR)
- CMRR = $\frac{1\mathrm{V}}{10\mu\mathrm{V}} = 10^5 = 100$ dB

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ANALOG DEVICES

Low Cost Low Power Instrumentation Amplifier

AD620

FEATURES

Easy to use
- **Gain set with one external resistor (Gain range 1 to 10,000)**
- **Wide power supply range (±2.3 V to ±18 V)**
- **Higher performance than 3 op amp IA designs**
- **Available in 8-lead DIP and SOIC packaging**
- **Low power, 1.3 mA max supply current**

Excellent dc performance (B grade)
- **50 µV max, input offset voltage**
- **0.6 µV/°C max, input offset drift**
- **1.0 nA max, input bias current**
- **100 dB min common-mode rejection ratio (G = 10)**

Low noise
- **9 nV/√Hz @ 1 kHz, input voltage noise**
- **0.28 µV p-p noise (0.1 Hz to 10 Hz)**

Excellent ac specifications
- **120 kHz bandwidth (G = 100)**
- **15 µs settling time to 0.01%**

CONNECTION DIAGRAM

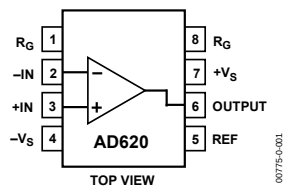

Figure 1. 8-Lead PDIP (N), CERDIP (Q), and SOIC (R) Packages

PRODUCT DESCRIPTION

The AD620 is a low cost, high accuracy instrumentation amplifier that requires only one external resistor to set gains of 1 to 10,000. Furthermore, the AD620 features 8-lead SOIC and DIP packaging that is smaller than discrete designs and offers lower power (only 1.3 mA max supply current), making it a good fit for battery-powered, portable (or remote) applications.

The AD620, with its high accuracy of 40 ppm maximum

100 dB min common-mode rejection ratio

Amplifier Requirements

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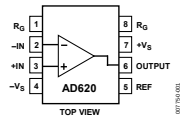

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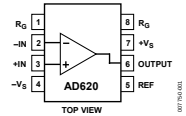

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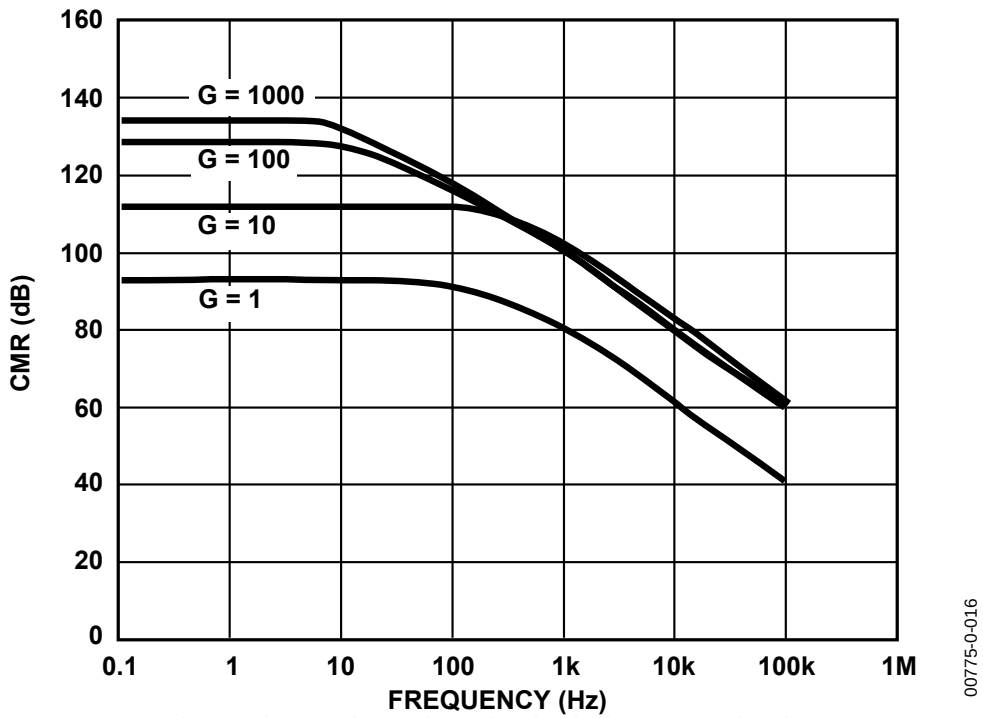
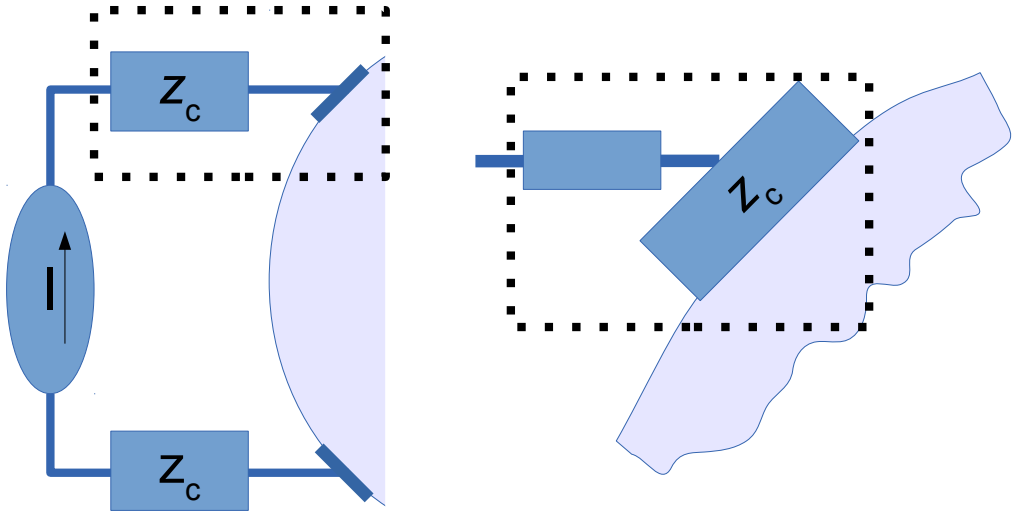


What is contact impedance?



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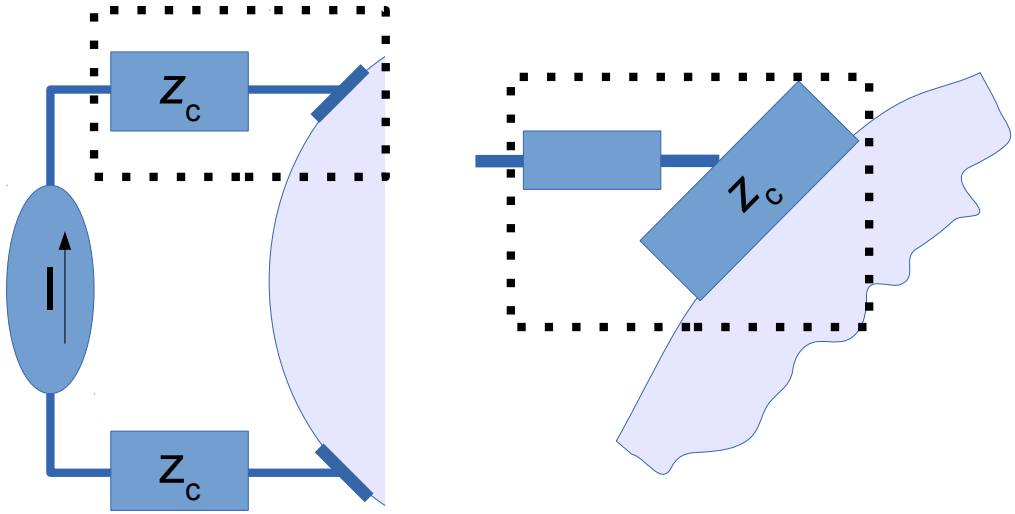

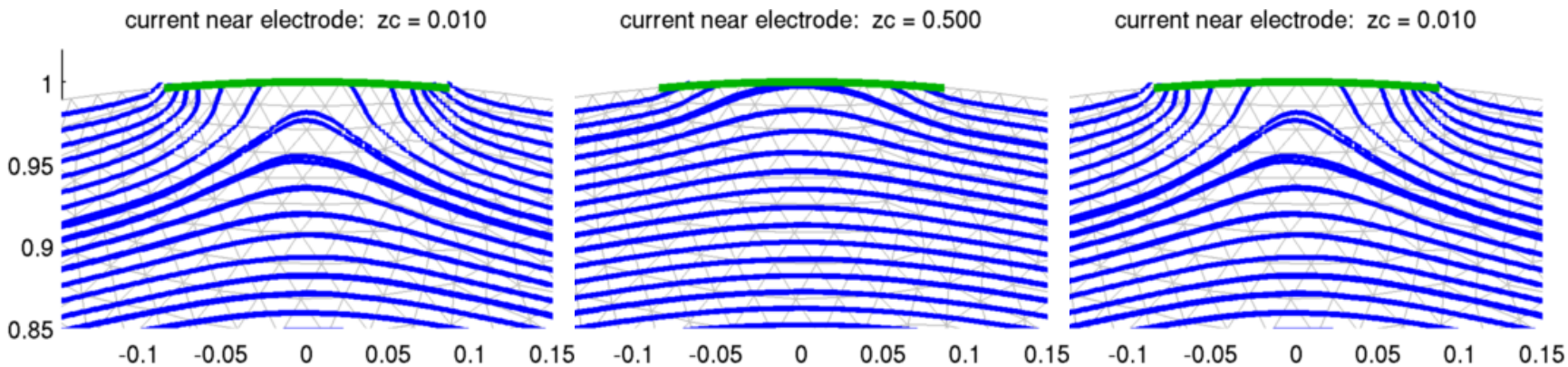

More challenges

- Crosstalk
- Amplifier input impedance
- . . .

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- . . .

Question:

- Geophysicists wont reuse a “hot” electrode for a few minutes. It becomes polarized. Why do we?

Inverse Problems: EIT

Why is EIT difficult?

Inverse Problems: EIT

Why is EIT difficult?

What are we doing about it?

Inverse Problems: EIT

Why is EIT difficult?

What are we doing about it?

We = the EIT community

Inverse Problems: EIT

Why is EIT difficult?

What are we doing about it?

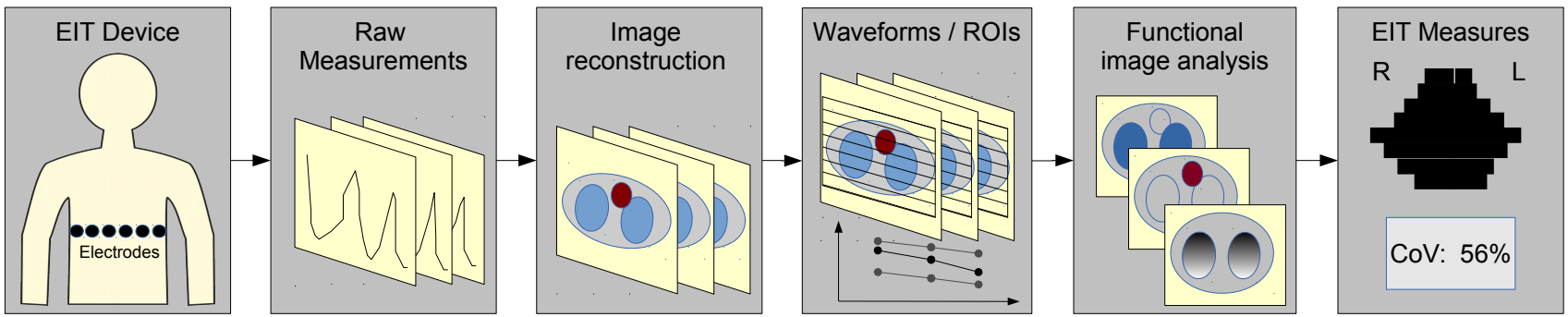
We = the EIT community

- Imaging −−
- Monitoring ++

What are we doing about it?

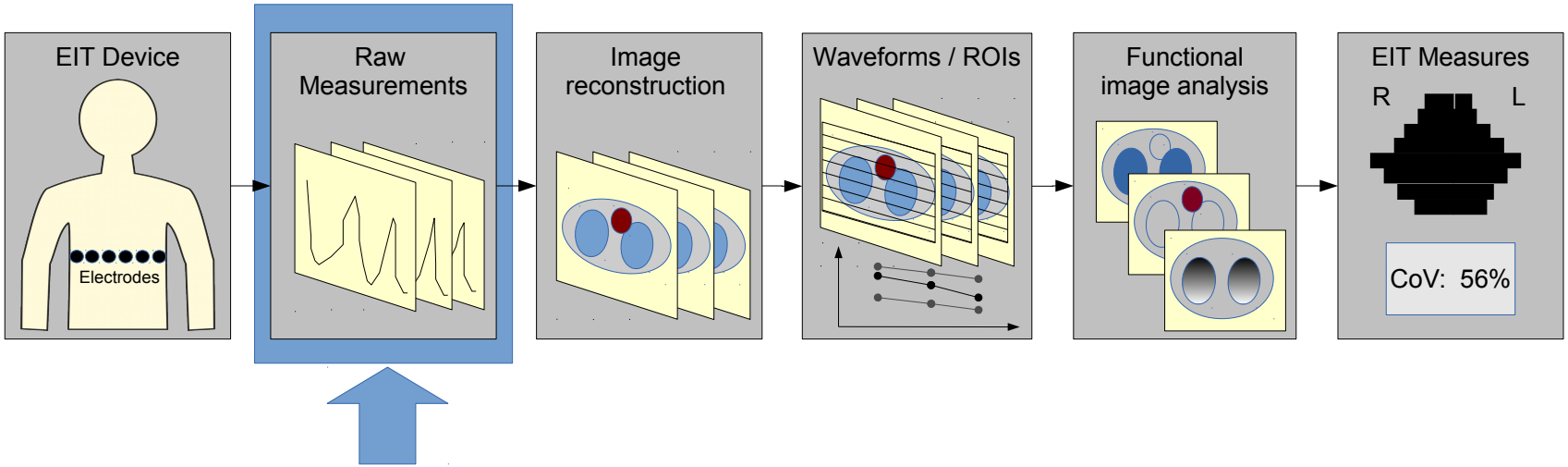
- Understanding EIT's sensitivity and limitations
- Developing novel measurement protocols and analysis methodologies

Analysis “pipeline”



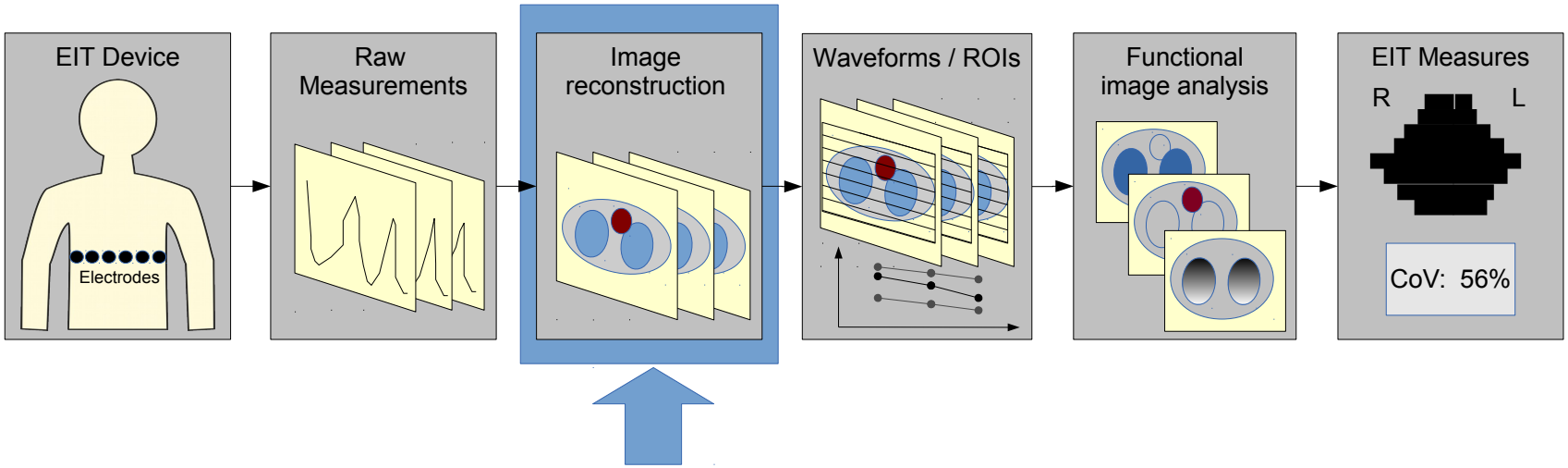
(Thanks to Inéz Frerichs for helping elaborate this concept)

Raw Measurement



- Where to place electrodes?
- “Off-plane” contributions?
- Frame rate?
- Stimulation / Measurement patterns?

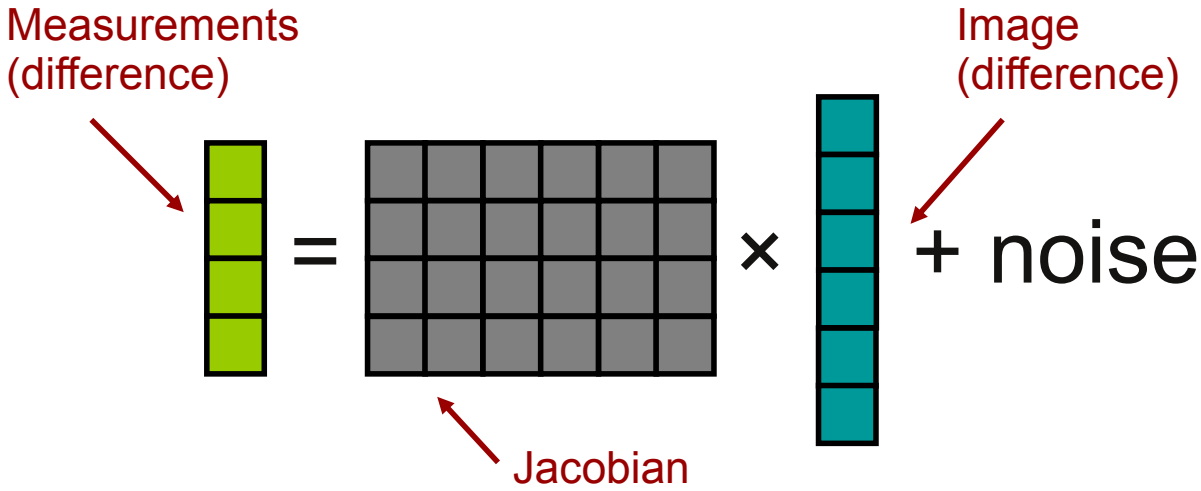
Raw Image Reconstruction



- Selection of reference/baseline
- Mixed absolute/difference algorithms
- Electrode position/movement
- Electrode errors
- Data Quality

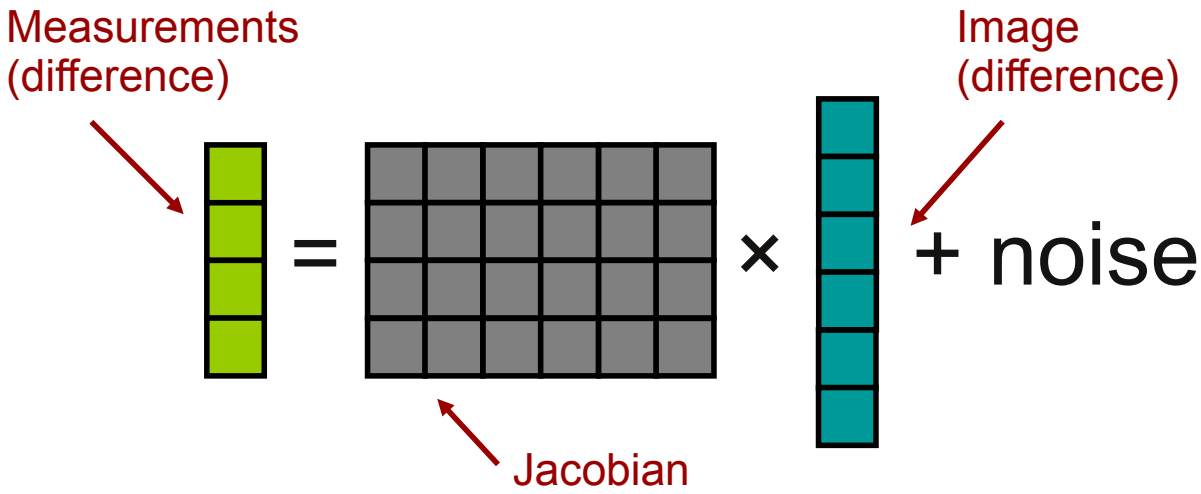
Reconstruction in Pictures

- Forward Problem

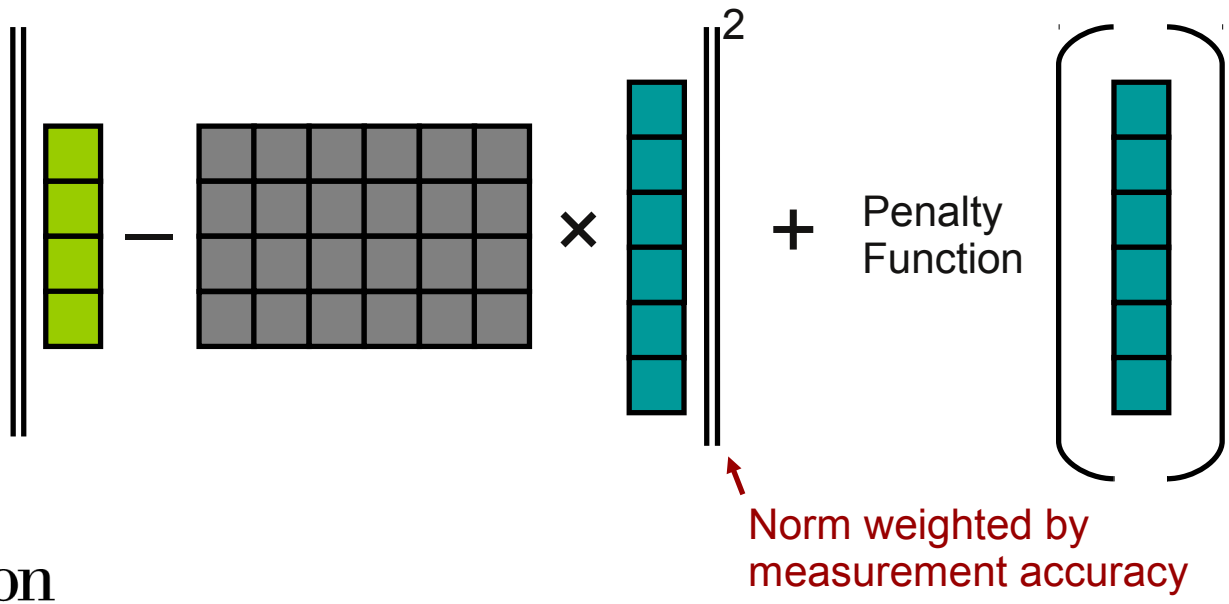


Reconstruction in Pictures

- Forward Problem

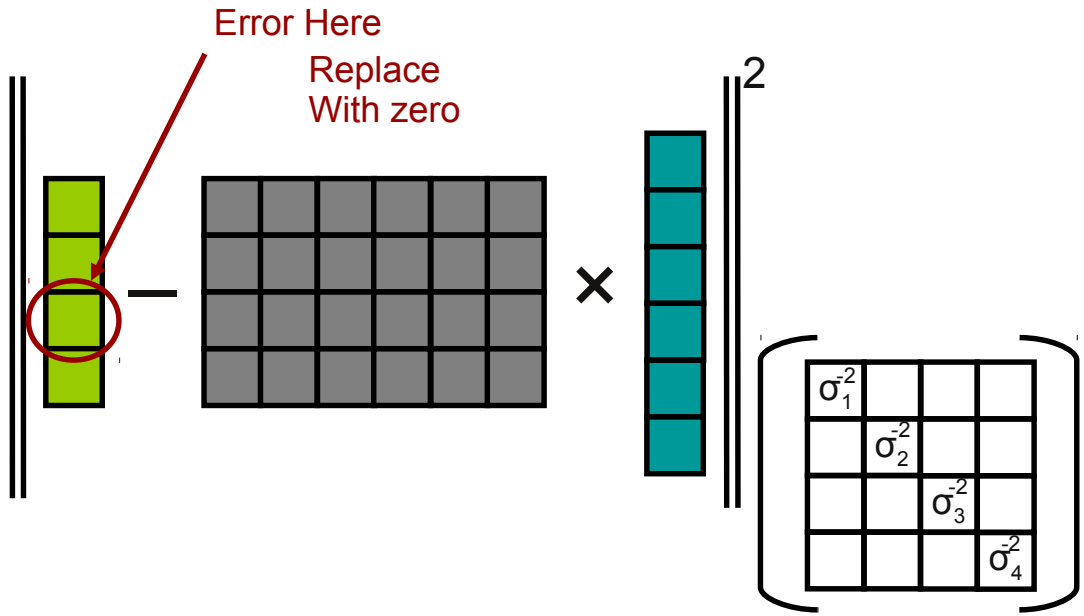


- Linear Solution: Minimize norm



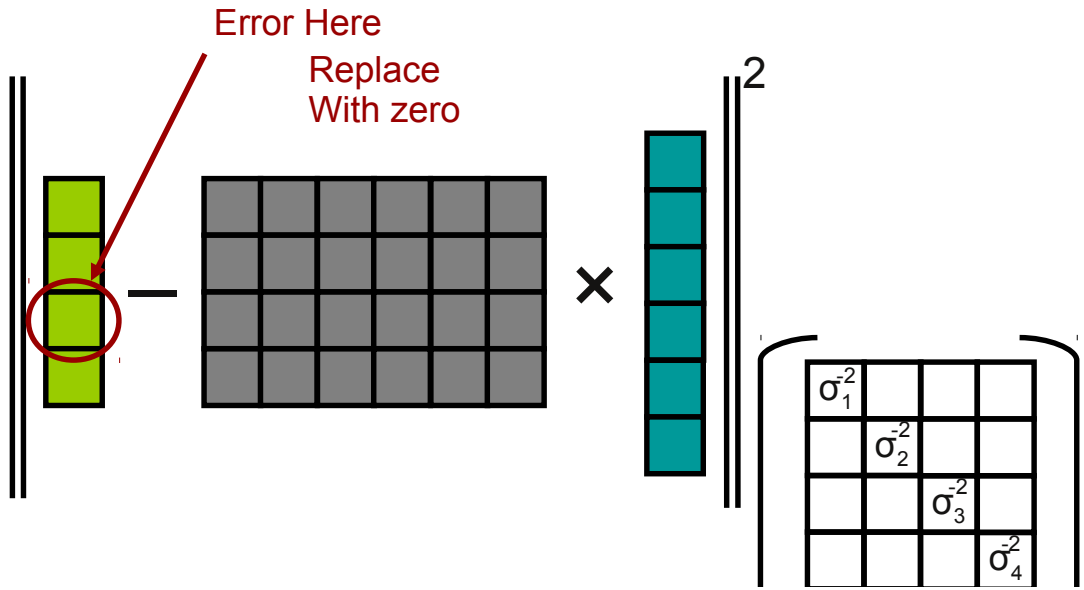
Reconstruction with Data Errors

"Traditional" Solution

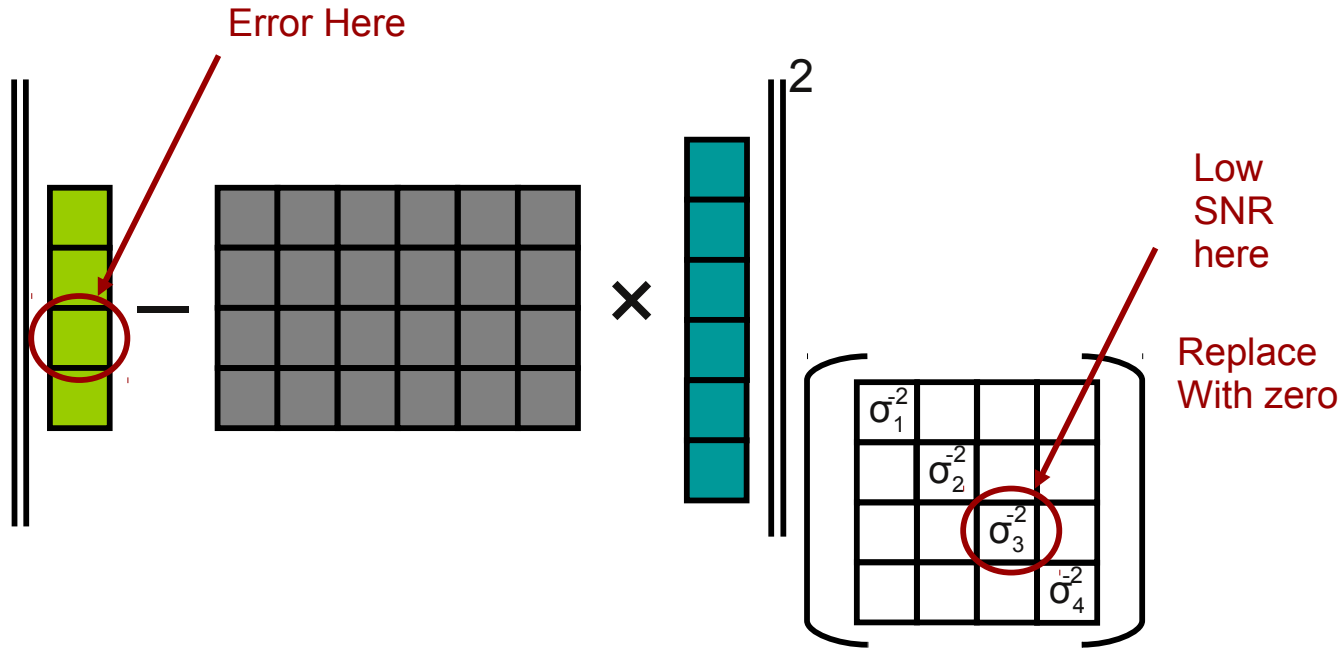


Reconstruction with Data Errors

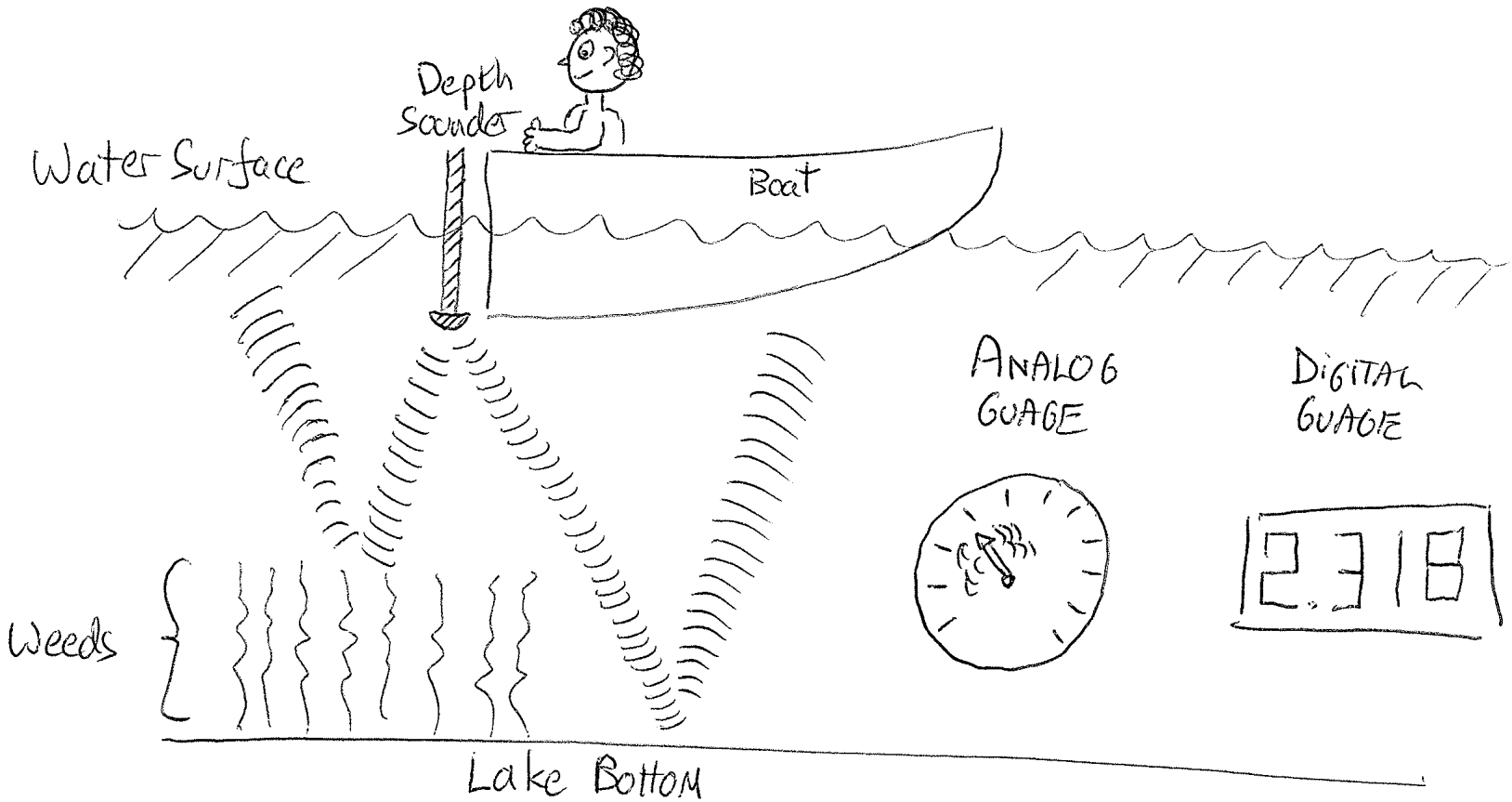
"Traditional" Solution



Error Model Solution



Data Quality

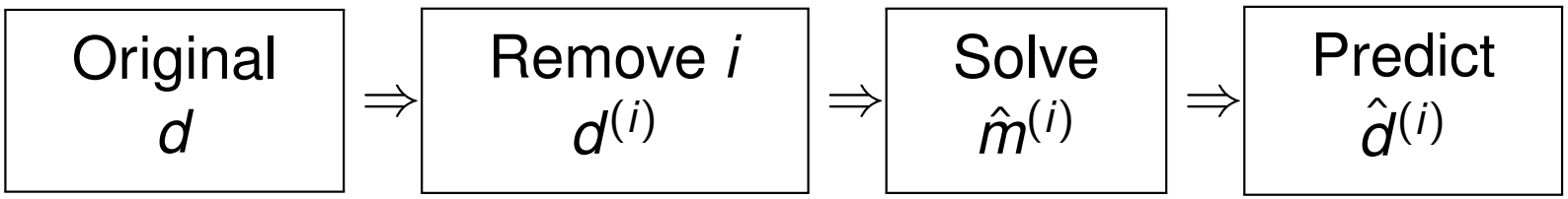


Depth Sounder – with analog and digital guages

Data Quality Measure: Concept

Concept: High Quality Data are Consistent

Idea: predict each data point from all others

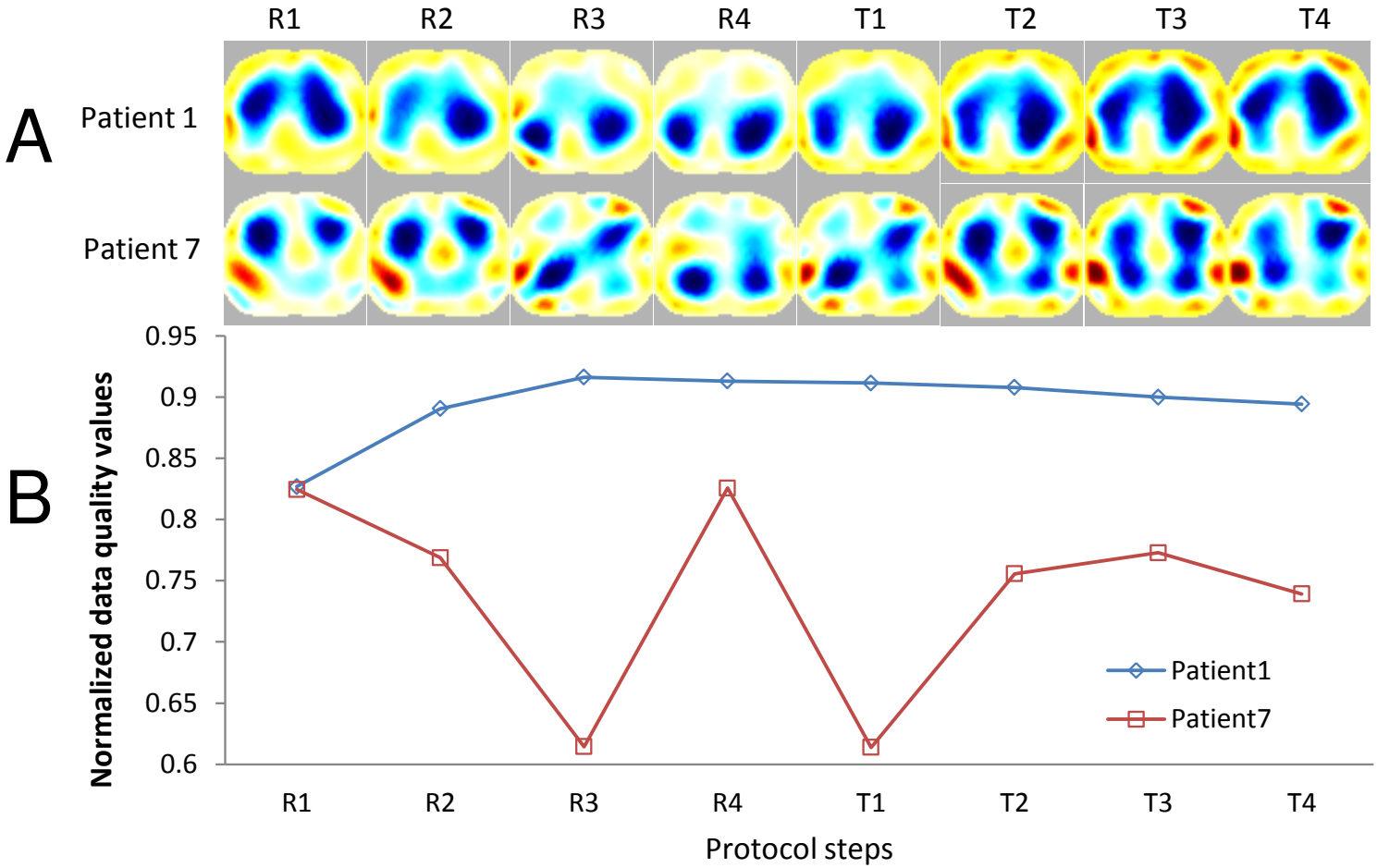


Calculate error

$$\epsilon_i = d_i - \hat{d}_i^{(i)}$$

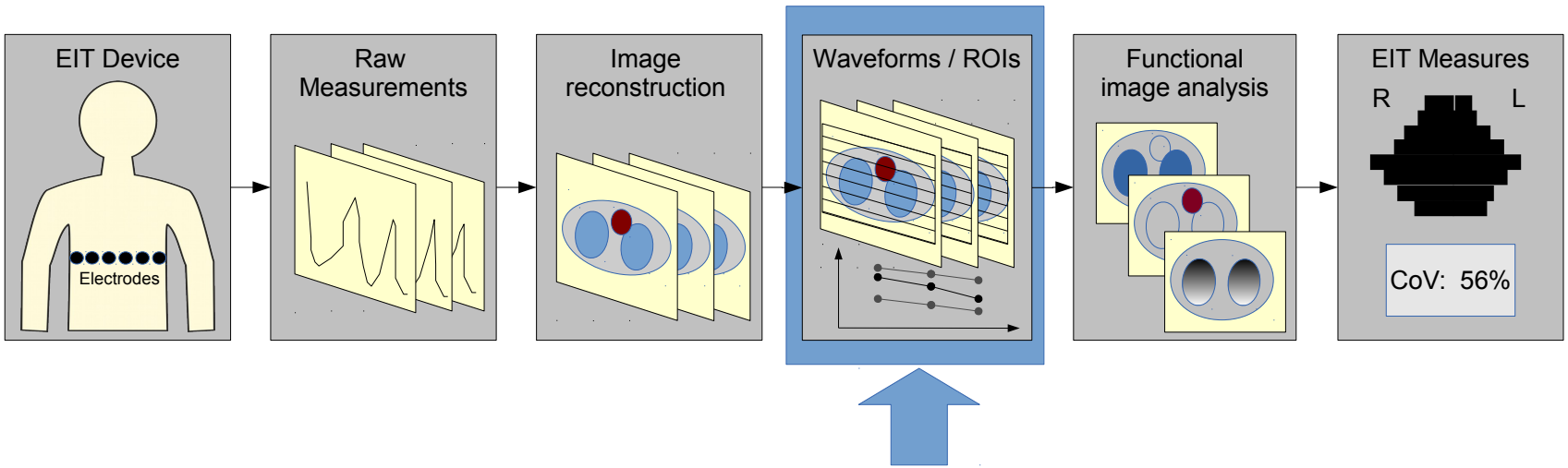
Example: Data quality measures

(R1–R4 — recruitment: PEEP⇑, T1–T4 — titration: PEEP⇓).



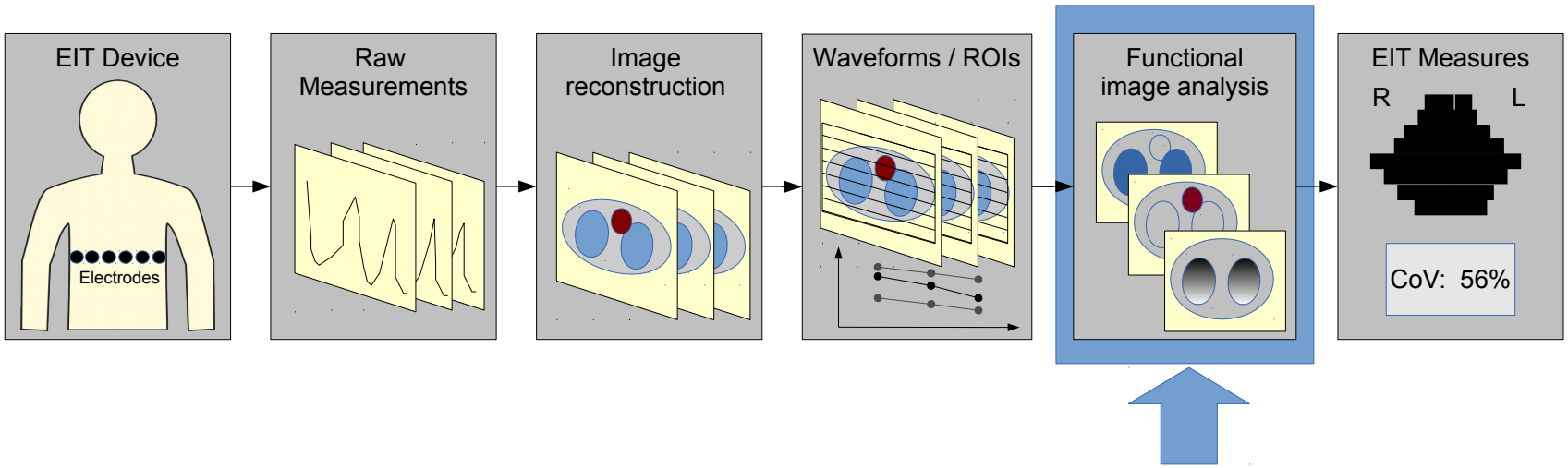
Clinical data (Wolf, *Pediatr Crit Care Med*, 2012) and data quality metric for each stage of the protocol. *A*: EIT, *B*: data quality.

ROIs and Waveforms



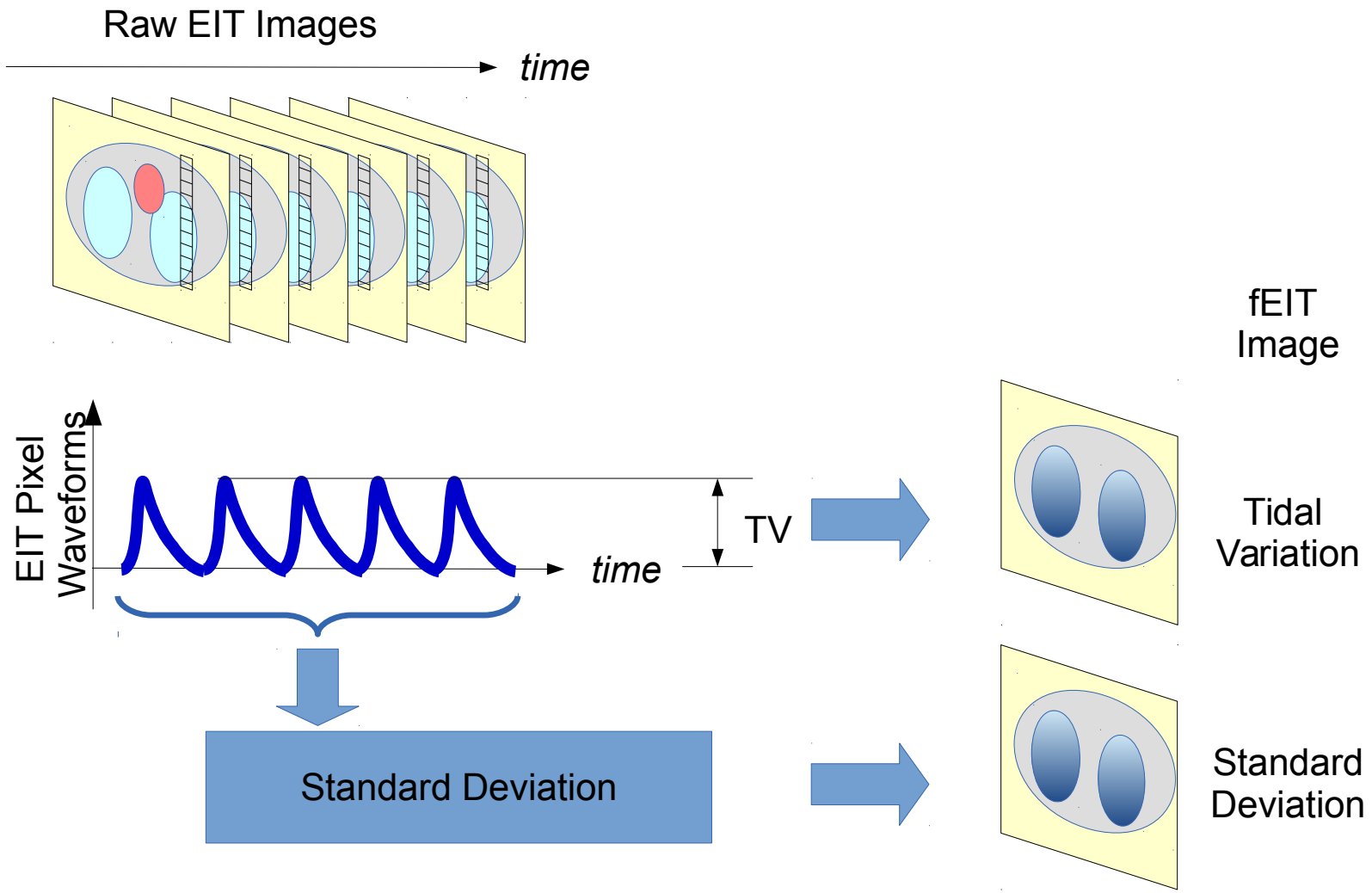
- Lung ROIs
- Anterioposterior direction

function EIT – fEIT

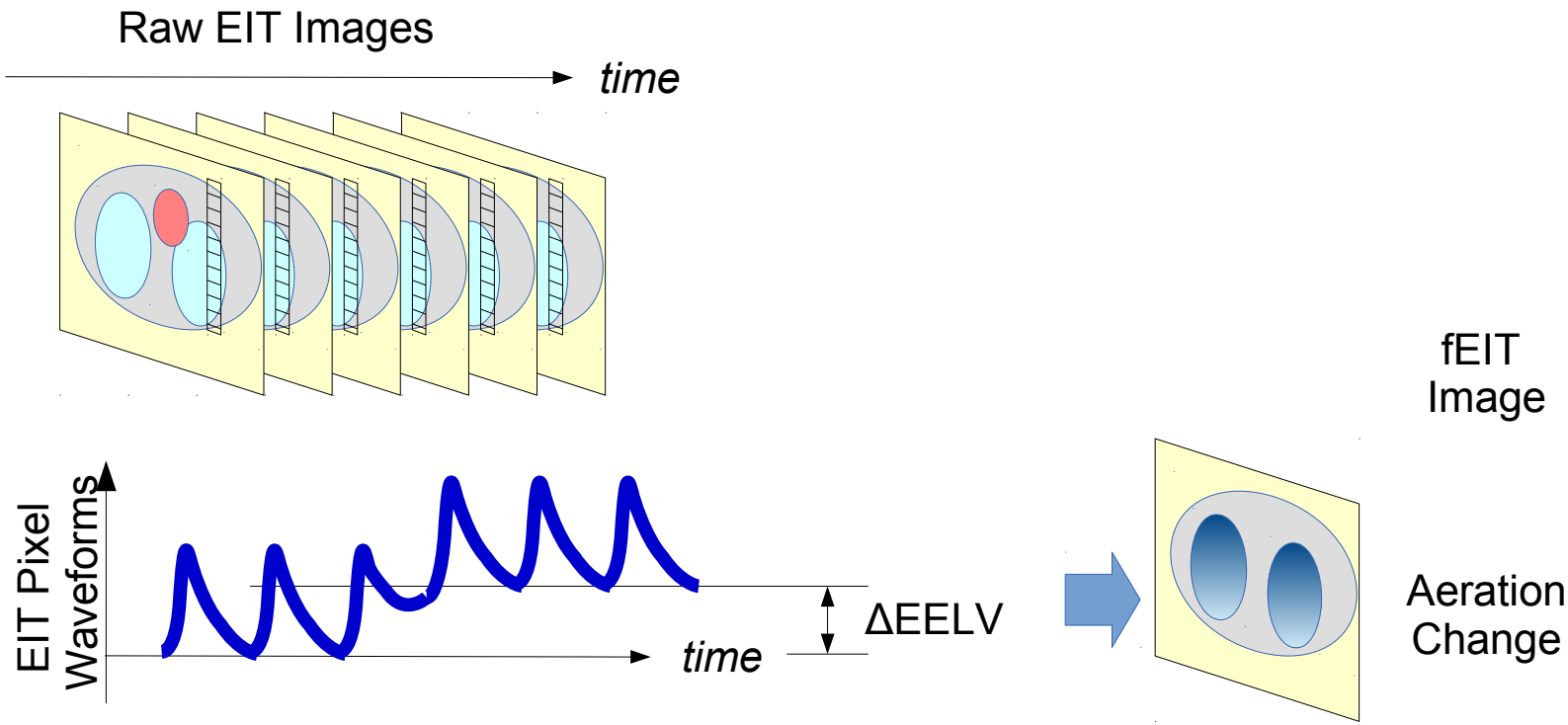


- From time sequence – generate image representing specific physiology

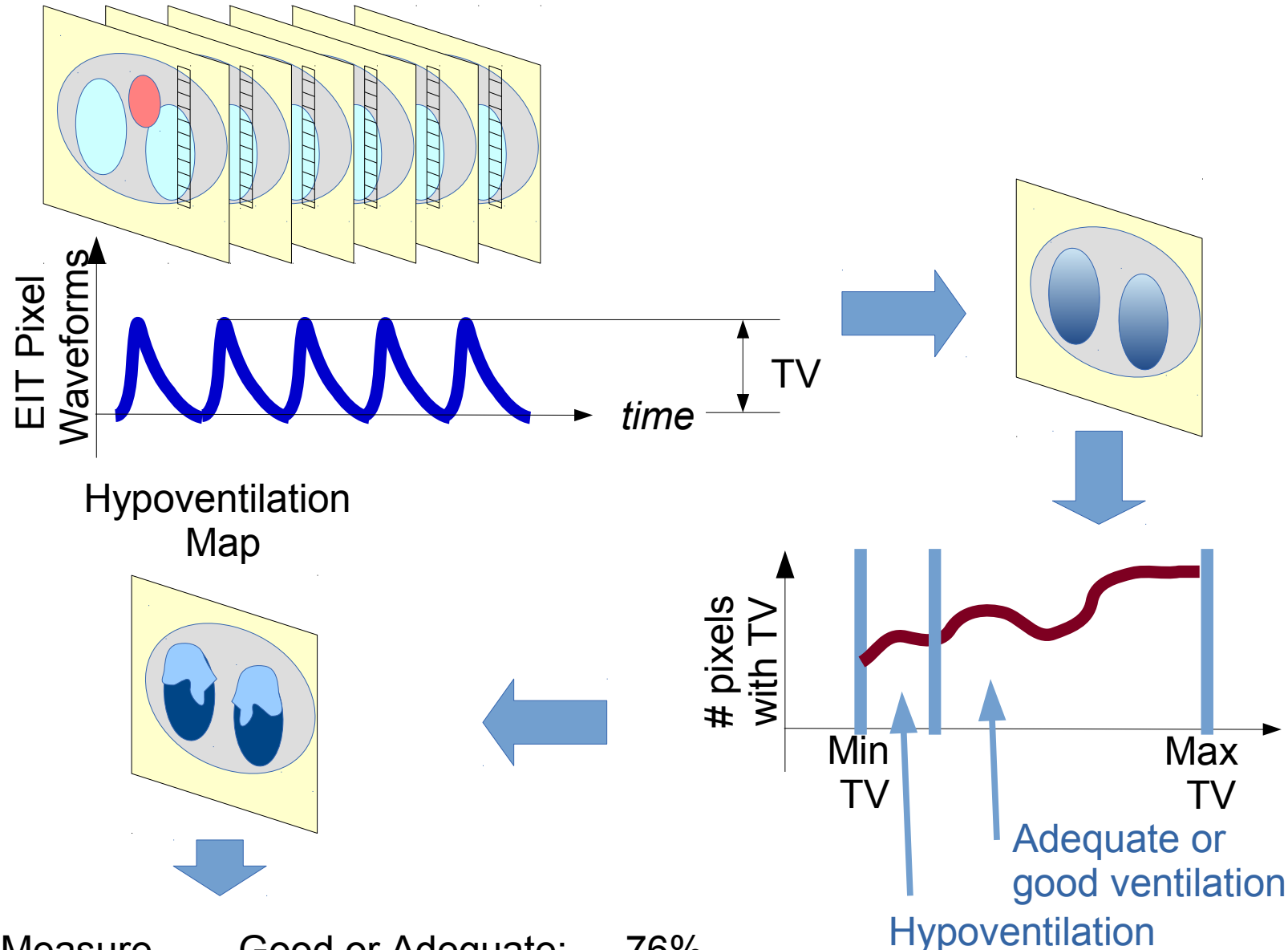
functional EIT (fEIT) images (Tidal Variation)



functional EIT (fEIT) images (Aeration Change)



functional EIT (fEIT) images (Hypo-ventilated lung)



EIT Measure		
	Good or Adequate:	76%
	Hypoventilated:	24%

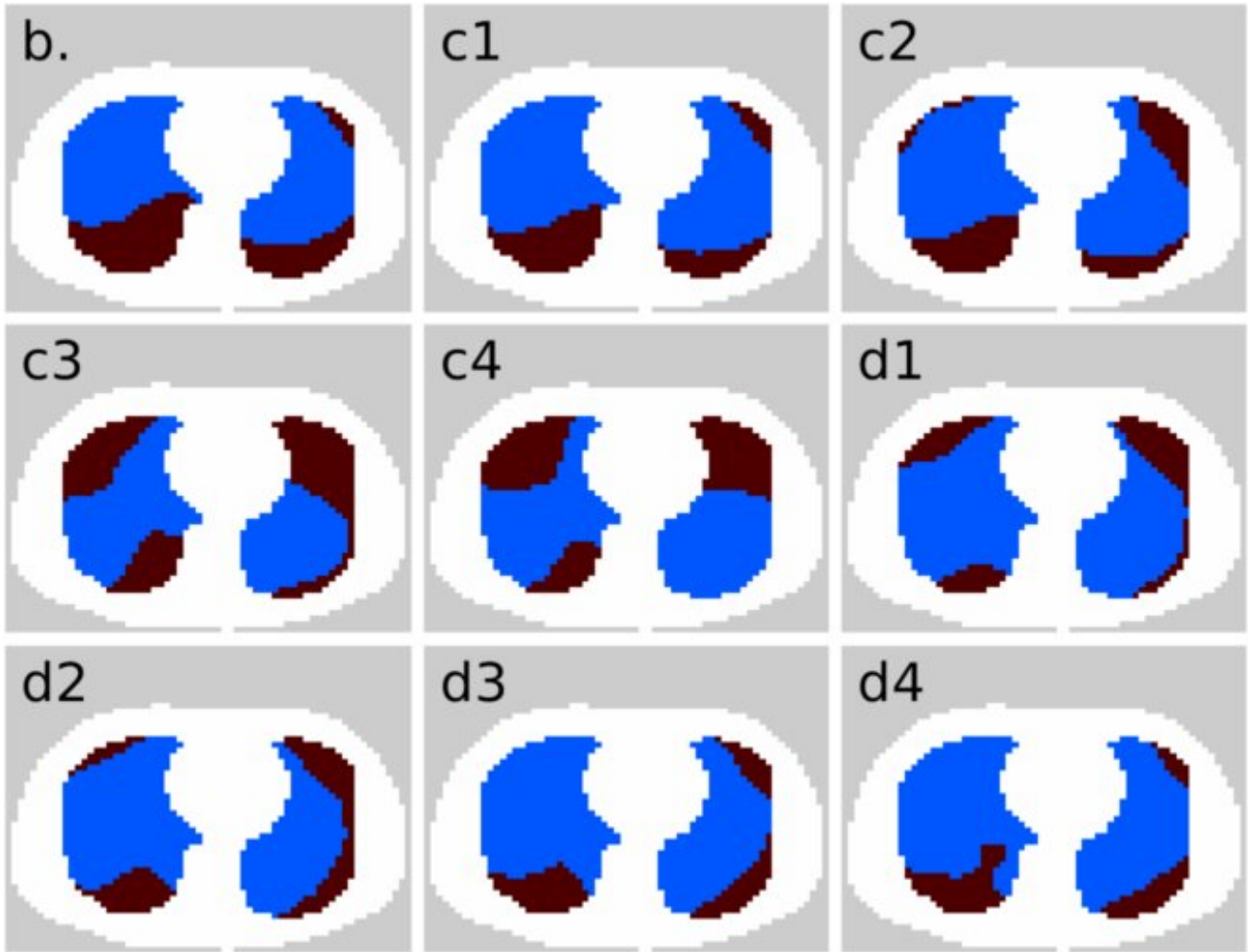
functional EIT (fEIT) images (Hypo-ventilated lung)

Calculate TV and threshold

CODE:

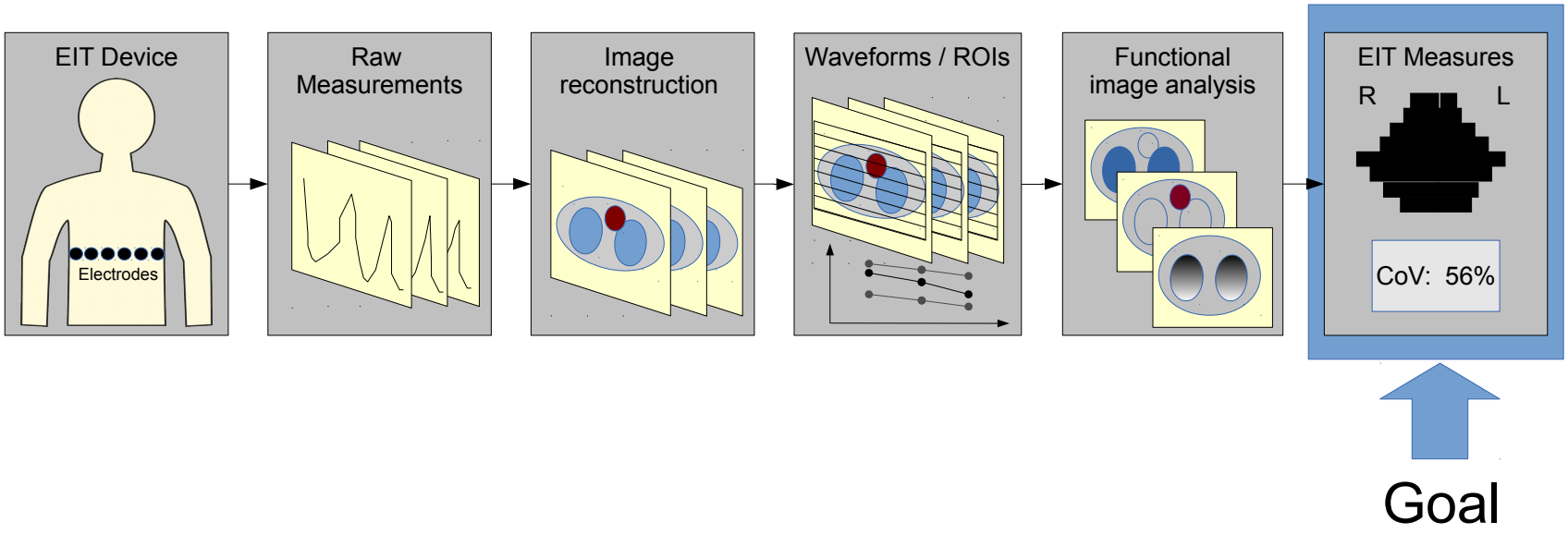
```
path= 'DATA/STUDYNAME/SUBJECT_1/YYYYMMDD/Eit/Viasys/'; dd= dir([path,'*.get']);
for idx = 1:length(dd);
   vv= eidors_readdata([path,dd(idx).name]);
   vr = mean(vv,2);
   img= inv_solve(imdl, vr, vv);
   img.calc_colours.backgnd=[1,1,1]*.8;
   ROI0 = ones(1,size(img.elem_data,1));
   [einsp,eexpi]= find_frc( img, ROI0, 13, '', 2);
   imgc = calc_slices(img); imgc(imgc==NaN) = 0;
   TV   = imgc(:,:,eexpi) - imgc(:,:,einsp);
   TV   = mean(TV,3).*ROI; % Air is +
   out = -ROI/2; % blue lungs
   out( (TV<.2*max(TV(:)))&(ROI==1) ) = 1;
   out = calc_colours(out, img); out(55:64,:)= [];
   subplot(3,3,idx); image(out); axis off
   text(3,7,dd(idx).name(6:7),'FontSize',16);
end

opt.vert_cut = 10; opt.vert_space = 5;
opt.horz_cut = 10; opt.horz_space = 5;
print_convert('analyse_step04a.jpg',opt);
```

fEIT image: Hypo-ventilated lung



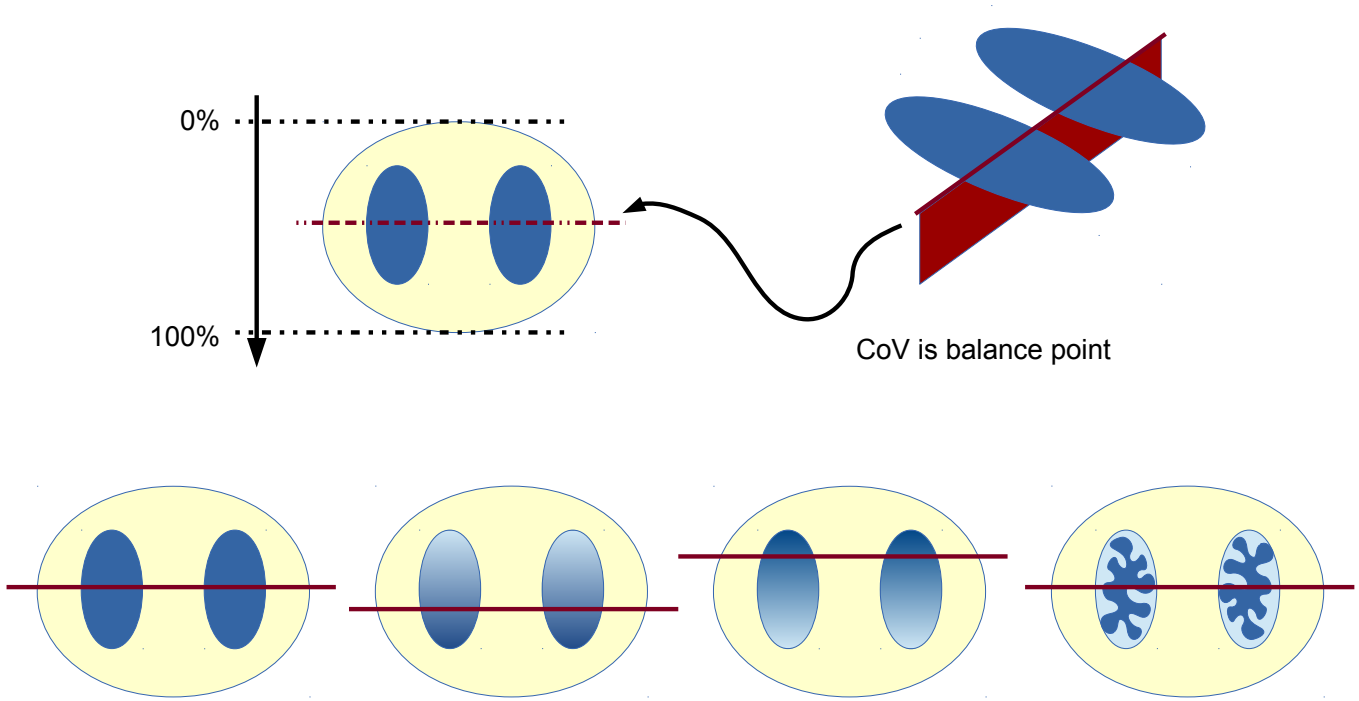
c1–c4 — recruitment: PEEP⇑, d1–d4 — titration: PEEP⇓

EIT Measures



- Average regional fEIT measures
- Characterizations of the spatial distribution of ventilation
- Examination-specific measures

#2A Measure of vertical distribution of ventilation



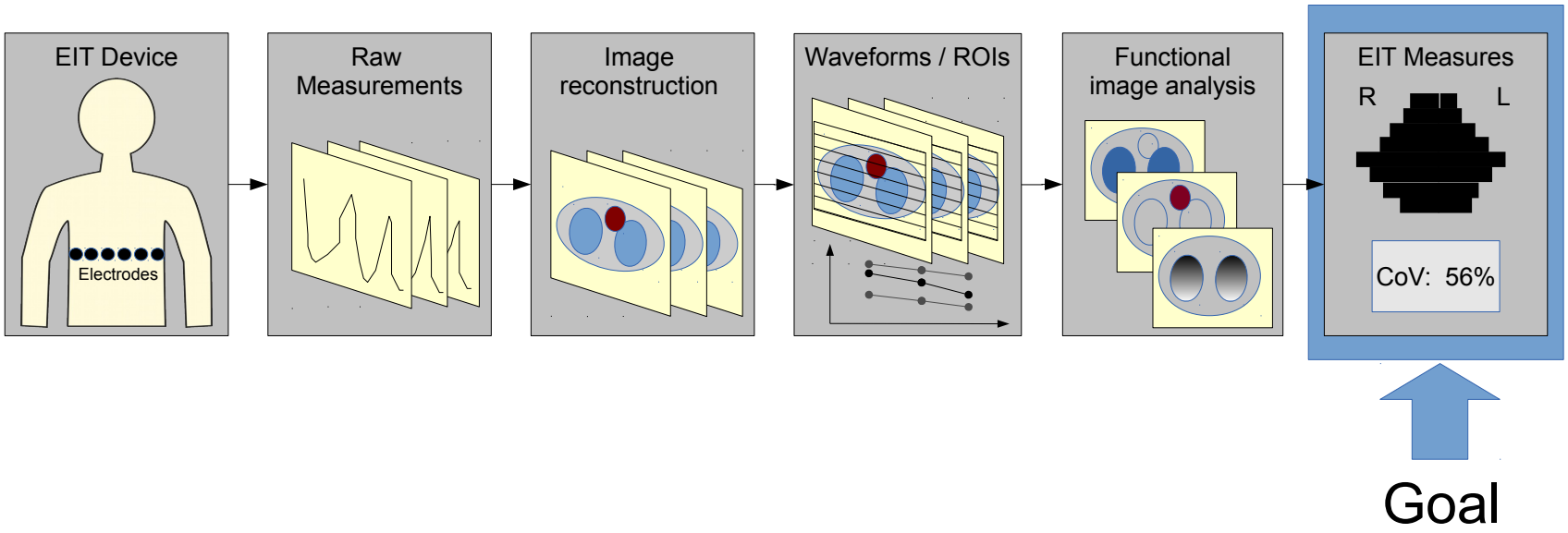
Measures of the anterioposterior distribution of ventilation

1. Center of Ventilation
2. Upper to Lower Ventilation Ratio[1]

[1] not recommended

Why is it difficult?
What are we doing about it?

EIT Measures



- Average regional fEIT measures
- Characterizations of the spatial distribution of ventilation
- Examination-specific measures
  - EIT measures using simultaneously measured signals
  - EIT measures using specific examination

Thank you

Traffic jam on the way to Carleton

Abstract: Currently, the most successful application of EIT is for imaging the thorax, where large movements in conductivity contrasting air and blood can be imaged over time. EIT imaging is difficult due to its low sensitivity to contrasts deep in the body, because of the diffuse nature of current propagation. EIT is thus sensitive to electrode properties, data quality, hardware imperfections and patient movement. To address these issues, several innovative strategies to analyze and interpret these data have been developed of the past few years. We introduce the concept of an EIT analysis pipeline, with stages of: measurements, raw images, waveforms, fEIT images, and measures. We will discuss recent progress in imaging the chest with EIT, and the image generation and interpretation strategies which are required.