COMP118 CW3: Mapping multi-contrast microstructural MRI of the placenta

Task 1 - Load and plot the MRI volumes and masks

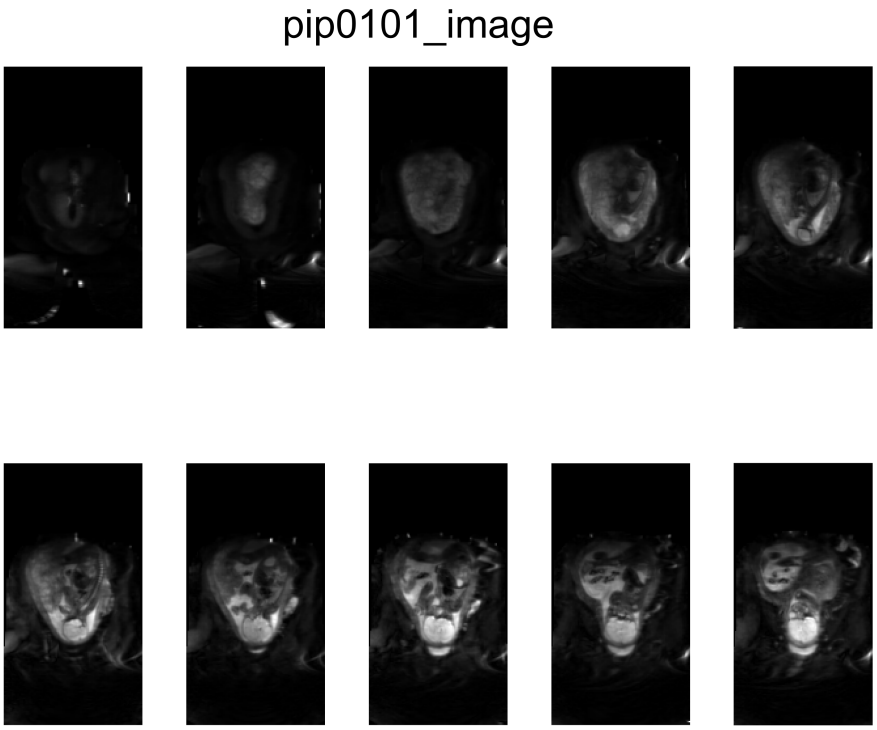
```
pip0101_image = im2double(niftiread("CW3\data\pip0101_20_20_1401_T2MEdiff_abs.alle.nii"));
pip0101_placenta_mask = niftiread("CW3\data\pip0101_placenta_mask.nii.gz");
pip0101_placenta_and_uterine_mask = niftiread("CW3\data\pip0101_placenta_and_uterine_wall_mask.

pip0120_image = im2double(niftiread("CW3\data\pip0120_20_20_2501_T2MEdiff_abs.alle.nii"));
pip0120_placenta_mask = niftiread("CW3\data\pip0120_placenta_mask.nii.gz");
pip0120_placenta_and_uterine_mask = niftiread("CW3\data\pip0120_placenta_and_uterine_wall_mask.

B1 = bwboundaries(pip0101_placenta_mask(:,:,7));
B2 = bwboundaries(pip0120_placenta_mask(:,:,7));

pip0101_size = size(pip0101_image)
```

```
pip0101_size = 1×4
   200   106    30   330
```

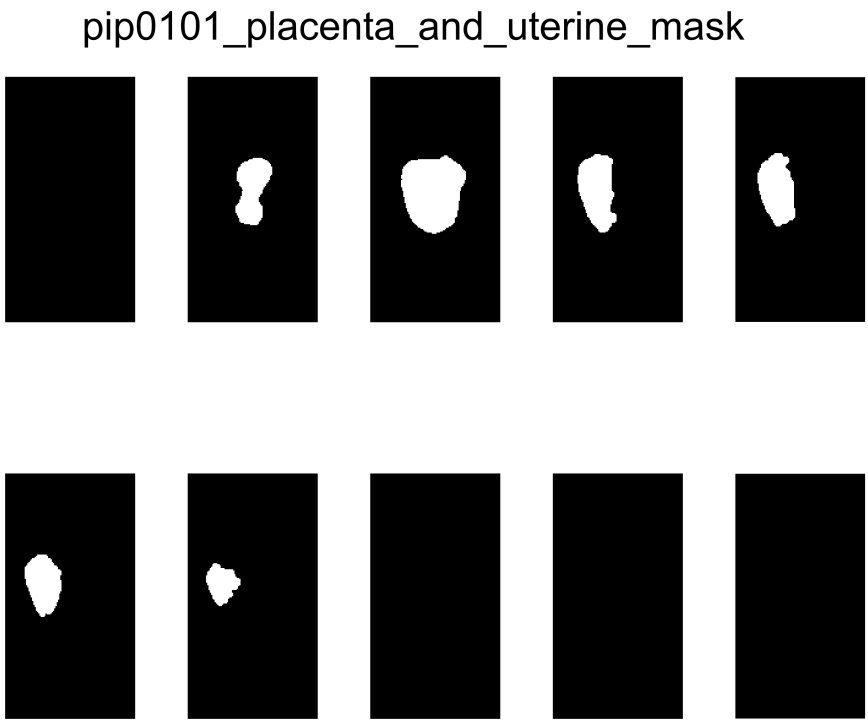
```
pip0120_size = size(pip0120_image)
```

```
pip0120_size = 1×4
   200   102    20   330
```

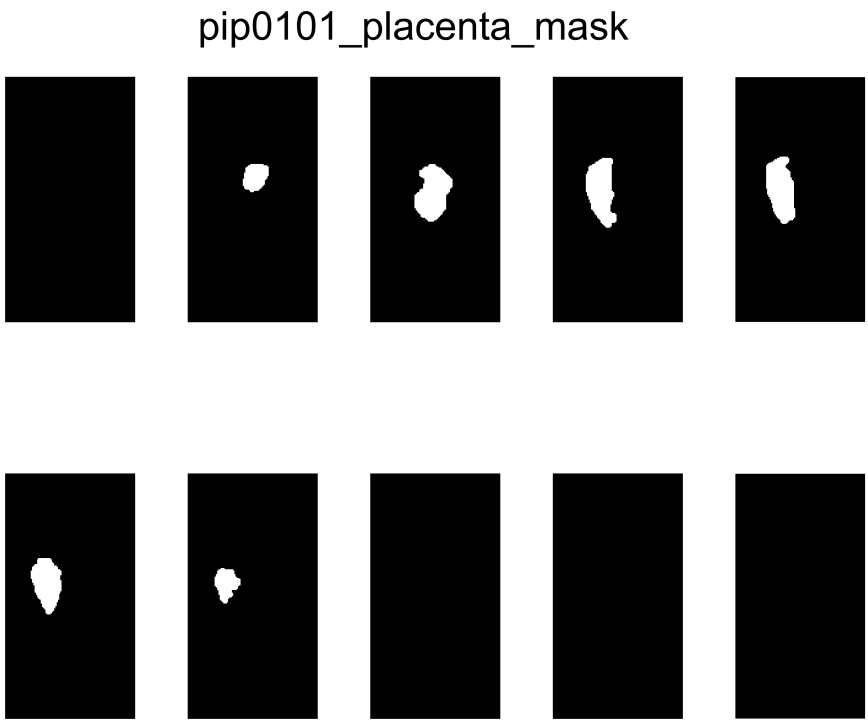
```
figure
sgtitle('pip0101\_image')
j= 1;
for i = 1:3:30
    subplot(2,5,j);
    img = pip0101_image(:,:,i,1);
    imshow(img,[0,max(img,[],"all")]);
    j = j + 1;
end
```




```
figure
sgtitle('pip0101\_placenta\_and\_uterine\_mask');
j= 1;
for i = 1:3:30
    subplot(2,5,j);
    imshow(pip0101_placenta_and_uterine_mask(:,:,i),[0,1]);
    j = j + 1;
end
```



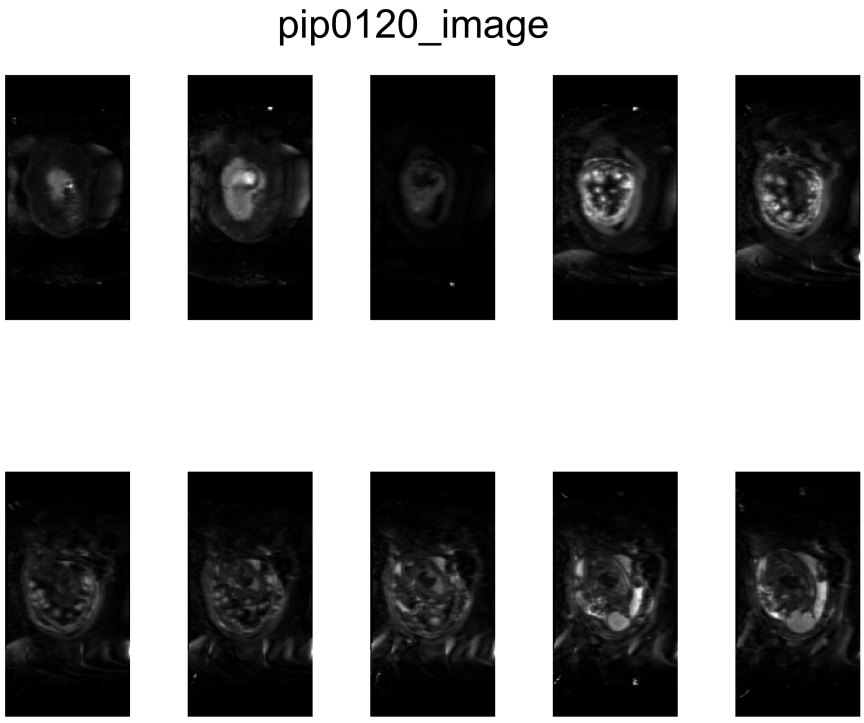

```
figure
sgtitle('pip0101\_placenta\_mask')
j= 1;
for i = 1:3:30
    subplot(2,5,j);
    imshow(pip0101_placenta_mask(:,:,i),[0,1]);
    j = j + 1;
end
```



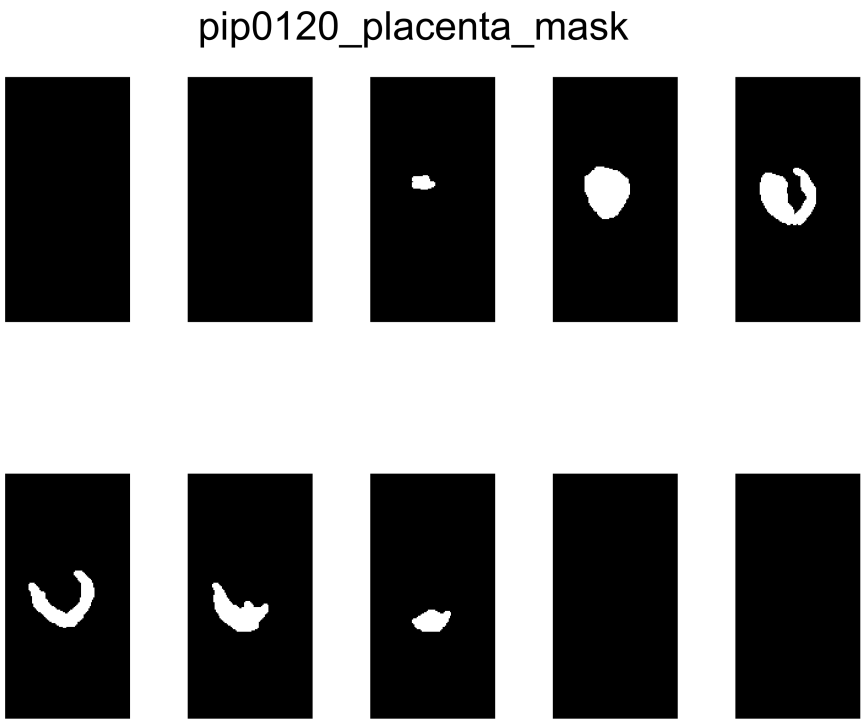

```
figure
sgtitle('pip0101\_placenta\_and\_uterine\_wall\_mask')
j= 1;
for i = 1:3:30
    subplot(2,5,j);
    imshow(pip0101_placenta_and_uterine_mask(:,:,i),[0,1]);
    j = j + 1;
end
```

pip0101_placenta_and_uterine_wall_mask

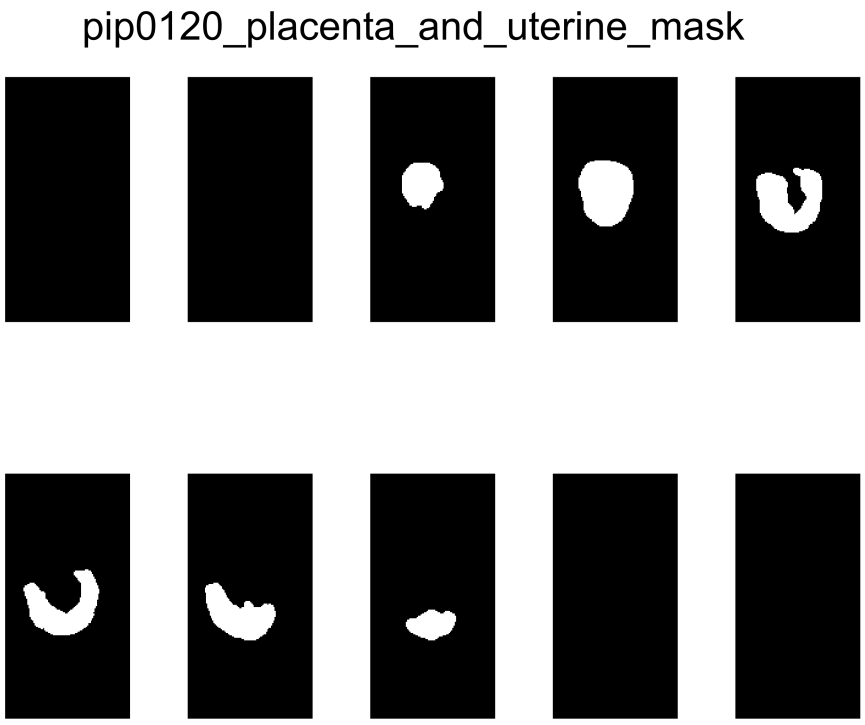
```
figure
sgtitle('pip0120\_image')
j= 1;
for i = 1:2:20
    subplot(2,5,j);
    img = pip0120_image(:,:,i,1);
    imshow(img,[0,max(img,[],"all")]);
    j = j + 1;
end
```



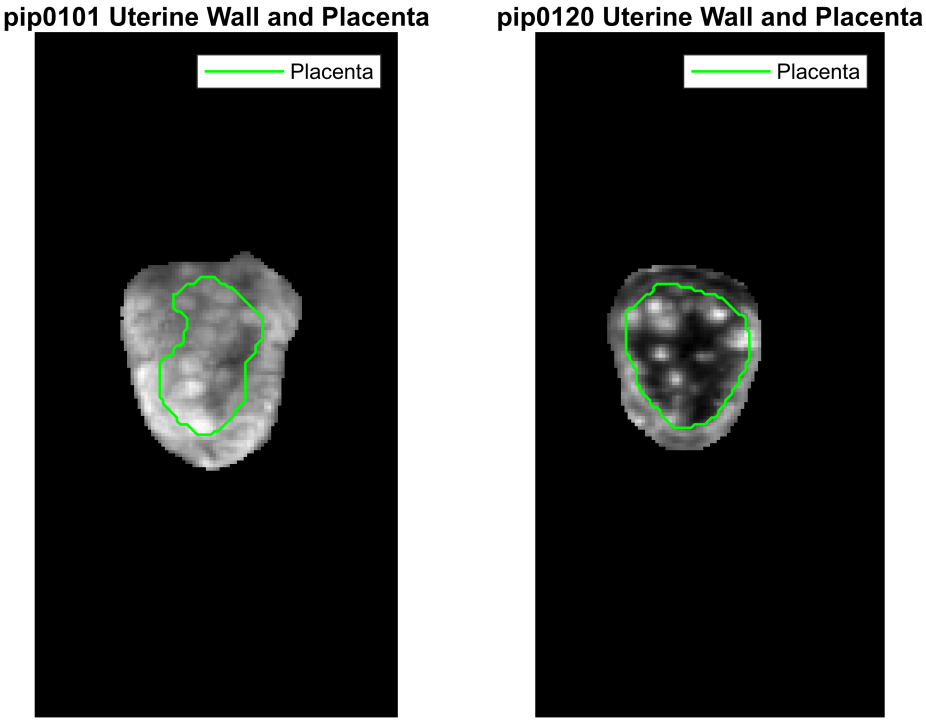

```
figure
sgtitle('pip0120\_placenta\_mask')
j= 1;
for i = 1:2:20
    subplot(2,5,j);
    imshow(pip0120_placenta_mask(:,:,i),[0,1]);
    j = j + 1;
end
```




```
figure
sgtitle('pip0120\_placenta\_and\_uterine\_mask')
j= 1;
for i = 1:2:20
    subplot(2,5,j);
    imshow(pip0120_placenta_and_uterine_mask(:,:,i),[0,1]);
    j = j + 1;
end
```

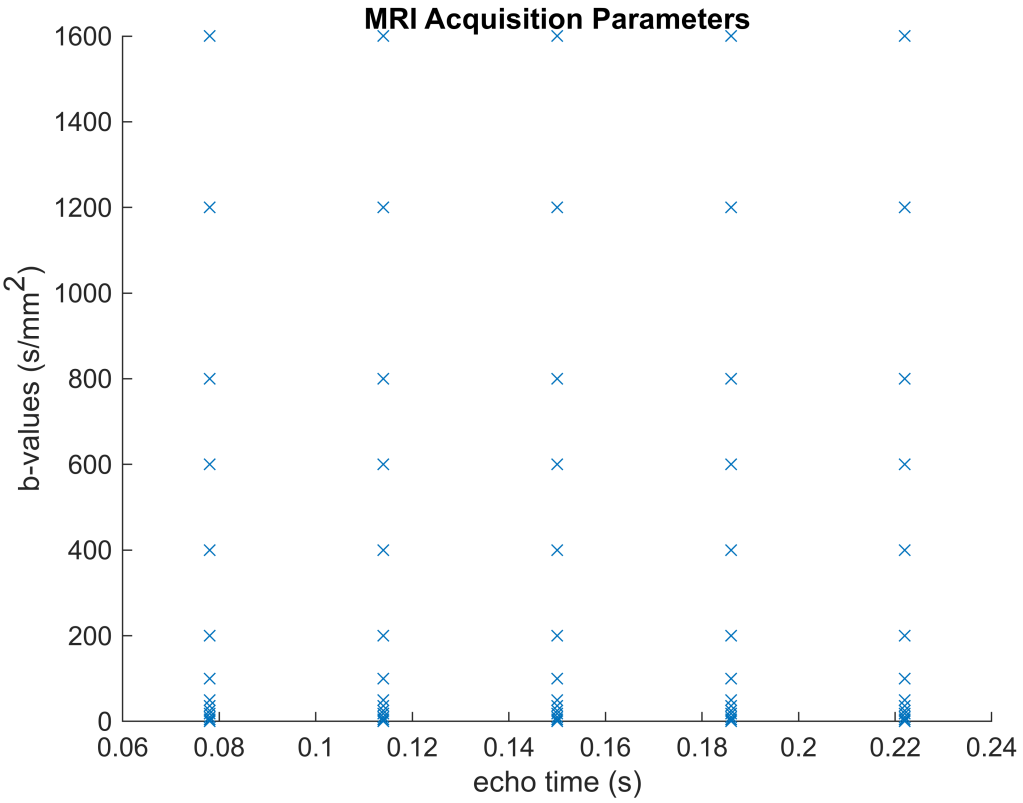



```
pip0101_placenta_and_uterine_image = pip0101_image(:,:,7,1) .* double(pip0101_placenta_and_uter
pip0120_placenta_and_uterine_image = pip0120_image(:,:,7,1) .* double(pip0120_placenta_and_uter
figure
subplot(1,2,1);
imshow(pip0101_placenta_and_uterine_image,[0,max(pip0101_placenta_and_uterine_image,[],"all")])
hold on
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 1)
hold off
legend("Placenta")
title("pip0101 Uterine Wall and Placenta");
subplot(1,2,2)
imshow(pip0120_placenta_and_uterine_image,[0,max(pip0120_placenta_and_uterine_image,[],"all")])
hold on
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 1)
hold off
legend("Placenta")
title("pip0120 Uterine Wall and Placenta");
saveas(gcf,"CW3\Figures\slice_7_utritne_wall_and_placentas",'epsc');
```



Task 2 – Load and plot the MRI acquisition parameters

```
figure("Name","Task2");
grad_echo = readmatrix("CW3\data\grad_echo.txt");
echo_times = grad_echo(:,5);
bvals = grad_echo(:,4);
scatter(echo_times,bvals,"x");
xlabel("echo time (s)");
ylabel("b-values (s/mm^2)");
title("MRI Acquisition Parameters");
saveas(gcf,"CW3\Figures\mri_acquisition_parmeters",'epsc');
```



Task 3 – Fit the combined T2*-ADC model

ROI Parameter Initialisation

```
Avox = squeeze(pip0101_image(100,49,7,:));
x0 = [0,10e-5,0.001]; % 1:S0, 2:d  3:T2_star
lower_bounds = [0,10e-5,0.001];
upper_bounds =[10e5,1,1];

mask = double(pip0101_placenta_and_uterine_mask);
mask(mask==0) = NaN;

ROI_mean = squeeze(mean(pip0101_image .* mask,[1,2,3],'omitnan'));

f = @(x)T2_star_ADC(x,ROI_mean,bvals,echo_times);
options = optimoptions(@fmincon,"Display","iter");

[x0,fval] = fmincon(f,x0,[],[],[],[],lower_bounds,upper_bounds,[],options)
```

```
Your initial point x0 is not between bounds lb and ub; FMINCON
shifted x0 to strictly satisfy the bounds.

                                             First-order      Norm of
 Iter F-count            f(x)  Feasibility   optimality         step
    0       4    1.612897e+05    0.000e+00    1.285e+03
    1      11    1.385890e+05    0.000e+00    2.379e+04    5.211e+01
    2      15    8.418819e+04    0.000e+00    3.259e+06    1.058e+01
```

```
    3      22    3.922478e+04    0.000e+00    1.621e+06    1.031e-01
    4      27    3.922301e+04    0.000e+00    3.636e+04    1.773e+00
    5      34    3.902528e+04    0.000e+00    5.790e+05    3.533e+00
    6      39    2.771671e+04    0.000e+00    2.041e+06    2.635e+01
    7      45    2.733067e+04    0.000e+00    8.096e+05    7.473e-01
    8      51    2.598838e+04    0.000e+00    1.422e+06    7.229e+00
    9      56    1.305205e+04    0.000e+00    2.823e+06    1.001e+02
   10      61    1.000875e+04    0.000e+00    5.666e+05    6.858e+00
   11      65    7.270051e+03    0.000e+00    8.592e+05    8.077e+00
   12      69    6.617171e+03    0.000e+00    1.803e+06    2.658e+01
   13      73    5.731294e+03    0.000e+00    1.057e+06    1.733e+00
   14      77    4.906469e+03    0.000e+00    4.477e+05    1.529e+01
   15      81    3.777986e+03    0.000e+00    2.474e+05    4.040e+01
   16      85    3.406952e+03    0.000e+00    2.867e+05    2.495e+01
   17      89    3.100324e+03    0.000e+00    2.715e+05    2.445e+01
   18      93    3.019197e+03    0.000e+00    3.147e+05    3.020e+01
   19      97    2.977983e+03    0.000e+00    5.810e+04    4.205e+00
   20     101    2.966589e+03    0.000e+00    4.026e+04    6.932e+00
   21     105    2.961640e+03    0.000e+00    1.866e+04    7.834e+00
   22     109    2.961470e+03    0.000e+00    3.177e+02    8.571e-01
   23     113    2.961468e+03    0.000e+00    6.510e+01    1.769e-01
   24     117    2.961468e+03    0.000e+00    2.768e+01    3.236e-03
   25     121    2.961468e+03    0.000e+00    4.403e+00    9.879e-05
   26     125    2.961468e+03    0.000e+00    1.000e-01    7.845e-05
   27     129    2.961468e+03    0.000e+00    9.771e-02    1.527e-03

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.

<stopping criteria details>
x0 = 1×3
  354.7960    0.0022    0.0443
fval = 2.9615e+03
```

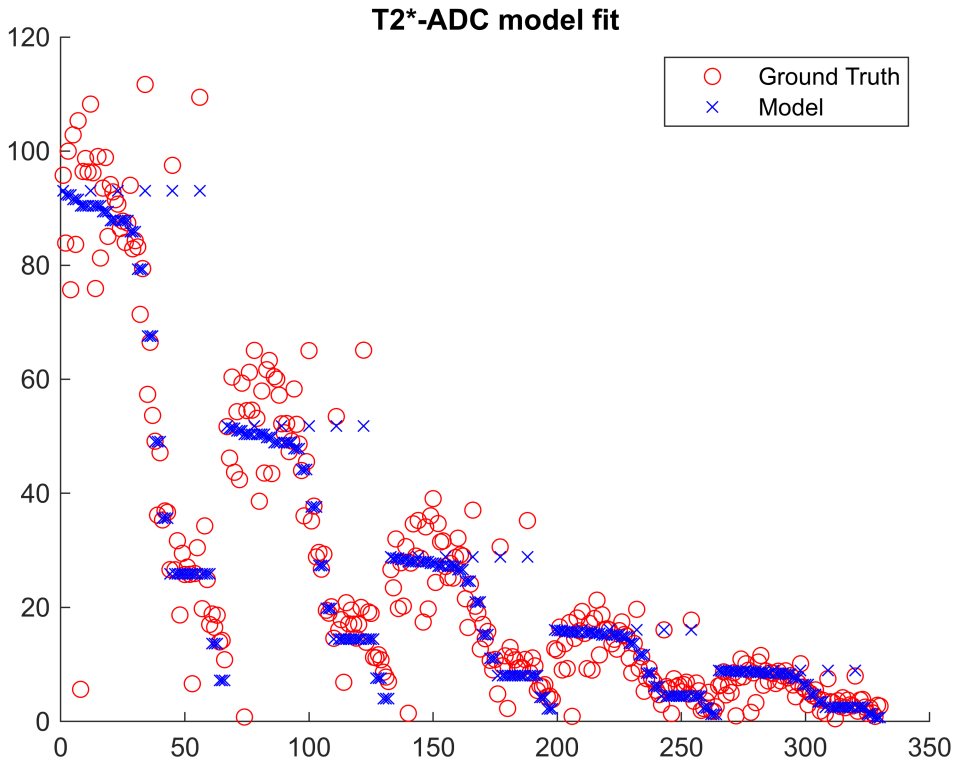
Fit to a single voxel

```
f = @(x)T2_star_ADC(x,Avox,bvals,echo_times);
[x,fval] = fmincon(f,x0,[],[],[],[],lower_bounds,upper_bounds,[],options)
```

```
                                          First-order      Norm of
 Iter F-count            f(x)  Feasibility   optimality         step
    0       4    1.072877e+05    0.000e+00    1.045e+07
    1      14    2.473074e+04    0.000e+00    1.538e+04    1.867e-02
    2      19    2.448627e+04    0.000e+00    3.097e+07    3.257e+01
    3      26    2.345345e+04    0.000e+00    1.710e+07    4.008e+01
    4      31    2.327543e+04    0.000e+00    2.943e+06    9.081e+01
    5      44    2.203918e+04    0.000e+00    6.660e+06    5.601e-03
    6      49    2.201687e+04    0.000e+00    6.348e+06    1.430e-01
    7      53    1.934454e+04    0.000e+00    3.200e+05    1.600e+01
    8      57    1.915586e+04    0.000e+00    1.005e+05    1.396e+01
    9      61    1.910073e+04    0.000e+00    2.553e+05    1.203e+01
   10      65    1.909668e+04    0.000e+00    4.038e+04    9.584e-03
   11      69    1.909657e+04    0.000e+00    1.003e+04    4.814e-01
   12      73    1.909657e+04    0.000e+00    1.212e+03    1.692e-02
   13      77    1.909657e+04    0.000e+00    5.075e+00    3.717e-03

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
```

```
satisfied to within the value of the constraint tolerance.

<stopping criteria details>
x = 1×3
  330.6033    0.0016    0.0615
fval = 1.9097e+04
```

```
xs = 1:length(Avox);
model = x(1) * exp(-echo_times/x(3)) .* exp(-bvals * x(2));
figure("Name","Single voxel T2_star_ADC fit");
scatter(xs,Avox,"o","CData",[1,0,0])
hold on
scatter(xs,model,"x","CData",[0,0,1]);
title("T2*-ADC model fit");
legend(["Ground Truth","Model"]);
hold off
```




```
mask_shape = size(pip0101_placenta_and_uterine_mask(:,:,7));
pip0101_S0_ADC_map = zeros(mask_shape);
pip0101_D_ADC_map = zeros(mask_shape);
pip0101_T_star_ADC_map = zeros(mask_shape);
pip0101_f_values_ADC_map = zeros(mask_shape);
options = optimoptions(@fmincon,"Display","off");

for i = 1:mask_shape(1)
    for j = 1:mask_shape(2)
```

```
        if pip0101_placenta_and_uterine_mask(i,j,7) == 1
            Avox = squeeze(pip0101_image(i,j,7,:));
            f = @(x)T2_star_ADC(x,Avox,bvals,echo_times);
            [x,fval] = fmincon(f,x0,[],[],[],[],lower_bounds,upper_bounds,[],options);
            pip0101_S0_ADC_map(i,j) = x(1);
            pip0101_D_ADC_map(i,j) = x(2);
            pip0101_T_star_ADC_map(i,j) = x(3);
            pip0101_f_values_ADC_map(i,j) = fval;
        else
            pip0101_S0_ADC_map(i,j) = NaN;
            pip0101_D_ADC_map(i,j) = NaN;
            pip0101_T_star_ADC_map(i,j) = NaN;
            pip0101_f_values_ADC_map(i,j) = NaN;
        end
    end
end
```

Region of interest paramiter initalization

```
pip0120_image_slice = pip0120_image(:,:,7,:);
mask = double(pip0120_placenta_and_uterine_mask);
mask(mask==0) = NaN;

ROI_mean = squeeze(mean(pip0120_image .* mask,[1,2,3],'omitnan'));

f = @(x)T2_star_ADC(x,ROI_mean,bvals,echo_times);
options = optimoptions(@fmincon,"Display","iter");

[x0,fval] = fmincon(f,x0,[],[],[],[],lower_bounds,upper_bounds,[],options)
```

```
                                          First-order      Norm of
 Iter F-count            f(x)  Feasibility  optimality         step
    0       4    3.055513e+04    0.000e+00    5.196e+06
    1       9    2.771387e+04    0.000e+00    3.484e+06    2.155e-02
    2      13    5.346281e+03    0.000e+00    1.137e+06    9.645e+01
    3      18    3.437760e+03    0.000e+00    1.155e+06    9.006e+00
    4      23    2.857011e+03    0.000e+00    1.378e+06    3.757e+00
    5      35    2.101809e+03    0.000e+00    4.097e+06    4.383e-03
    6      40    2.094813e+03    0.000e+00    4.075e+06    1.255e-01
    7      45    1.050067e+03    0.000e+00    8.905e+05    7.401e+01
    8      51    8.321930e+02    0.000e+00    3.933e+05    4.650e+01
    9      56    7.095540e+02    0.000e+00    7.023e+05    9.362e+01
   10      60    5.934410e+02    0.000e+00    5.141e+05    1.319e-01
   11      65    5.551197e+02    0.000e+00    5.764e+04    1.226e+01
   12      69    5.382587e+02    0.000e+00    7.659e+04    1.302e+01
   13      73    5.163048e+02    0.000e+00    1.181e+05    2.927e+01
   14      77    5.017344e+02    0.000e+00    5.416e+04    1.024e+01
   15      81    4.929555e+02    0.000e+00    2.341e+04    1.911e+01
   16      85    4.910378e+02    0.000e+00    8.754e+03    1.031e+01
   17      89    4.906651e+02    0.000e+00    3.386e+03    5.883e+00
   18      93    4.906432e+02    0.000e+00    8.289e+02    1.488e+00
   19      98    4.906426e+02    0.000e+00    1.598e+02    2.388e-01
   20     102    4.906426e+02    0.000e+00    7.782e+01    5.440e-02
   21     106    4.906426e+02    0.000e+00    6.892e+00    1.619e-03
   22     110    4.906426e+02    0.000e+00    1.810e-01    7.245e-04
```

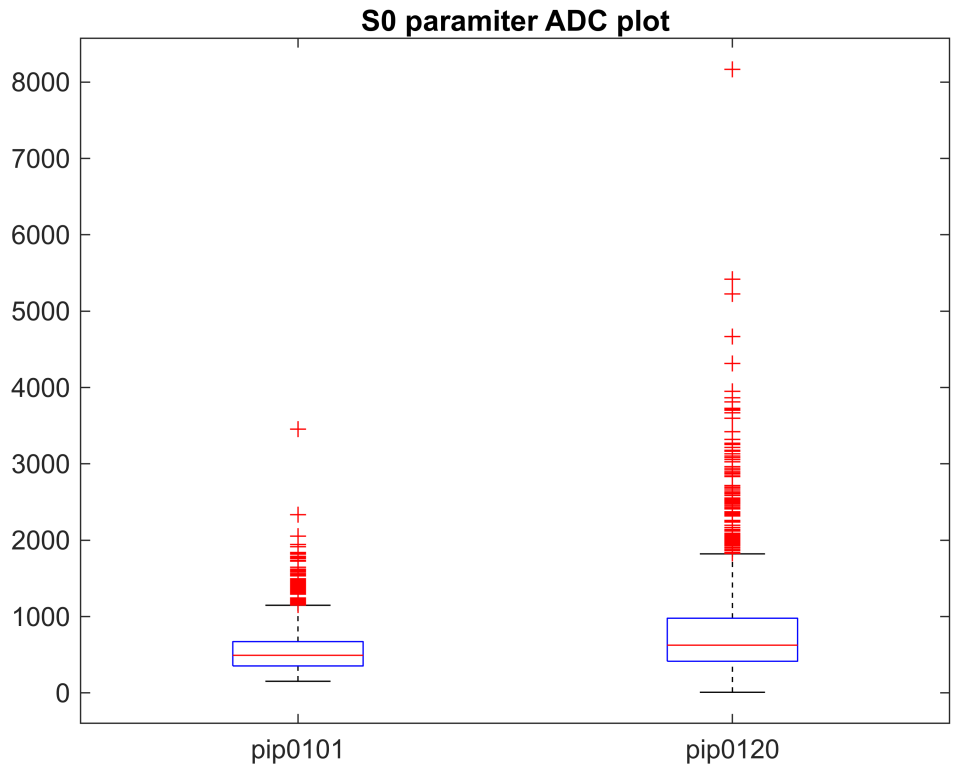
```
   23     114    4.906425e+02    0.000e+00    1.057e+00    1.335e-02
   24     122    4.906425e+02    0.000e+00    4.267e-04    1.440e-09

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.

<stopping criteria details>
x0 = 1×3
  444.2937    0.0017    0.0312
fval = 490.6425
```

```
mask_shape = size(pip0120_placenta_and_uterine_mask(:,:,7));
pip0120_S0_ADC_map = zeros(mask_shape);
pip0120_D_ADC_map = zeros(mask_shape);
pip0120_T_star_ADC_map = zeros(mask_shape);
pip0120_f_values_ADC_map = zeros(mask_shape);
options = optimoptions(@fmincon,"Display","off");

for i = 1:mask_shape(1)
    for j = 1:mask_shape(2)
        if pip0120_placenta_and_uterine_mask(i,j,7) == 1
            Avox = squeeze(pip0120_image(i,j,7,:));
            f = @(x)T2_star_ADC(x,Avox,bvals,echo_times);
            [x,fval] = fmincon(f,x0,[],[],[],[],lower_bounds,upper_bounds,[],options);
            pip0120_S0_ADC_map(i,j) = x(1);
            pip0120_D_ADC_map(i,j) = x(2);
            pip0120_T_star_ADC_map(i,j) = x(3);
            pip0120_f_values_ADC_map(i,j) = fval;
        else
            pip0120_S0_ADC_map(i,j) = NaN;
            pip0120_D_ADC_map(i,j) = NaN;
            pip0120_T_star_ADC_map(i,j) = NaN;
            pip0120_f_values_ADC_map(i,j) = NaN;
        end
    end
end
```

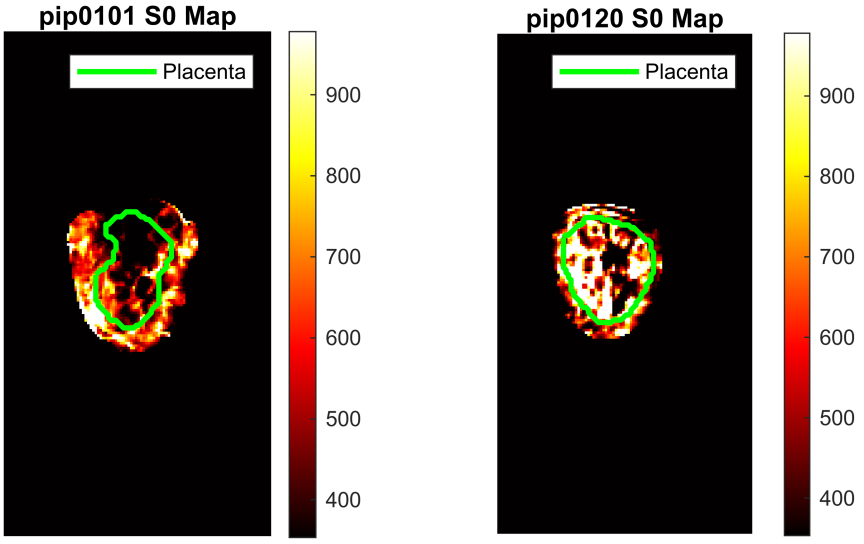
Task 4 – Compare maps for control and pre-eclampsia participants

Box plots of parameters

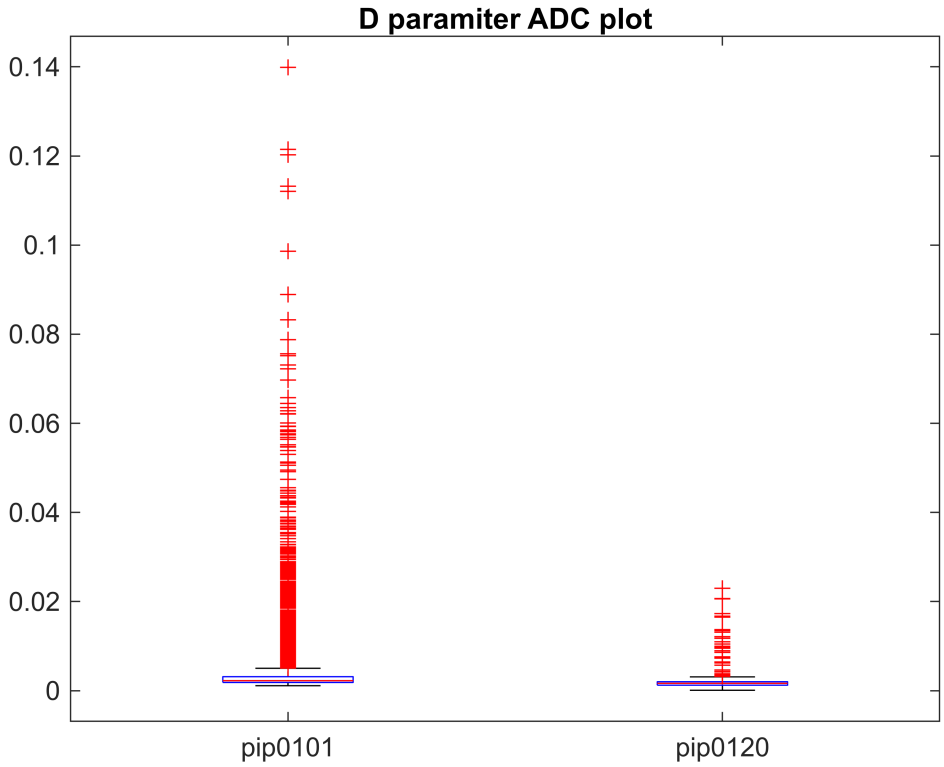
```
figure
x1 = pip0101_S0_ADC_map(~isnan(pip0101_S0_ADC_map));
x2 = pip0120_S0_ADC_map(~isnan(pip0120_S0_ADC_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("S0 paramiter ADC plot");
```




```
range = [quantile(x1,[.25 .75]) quantile(x2,[.25 .75])];
figure
subplot(1,2,1);
imshow(pip0101_S0_ADC_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 S0 Map");
colorbar;
legend("Placenta")
subplot(1,2,2);
imshow(pip0120_S0_ADC_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 S0 Map");
legend("Placenta")
colorbar;
saveas(gcf,"CW3\Figures\ADC_S0_maps",'epsc');
```

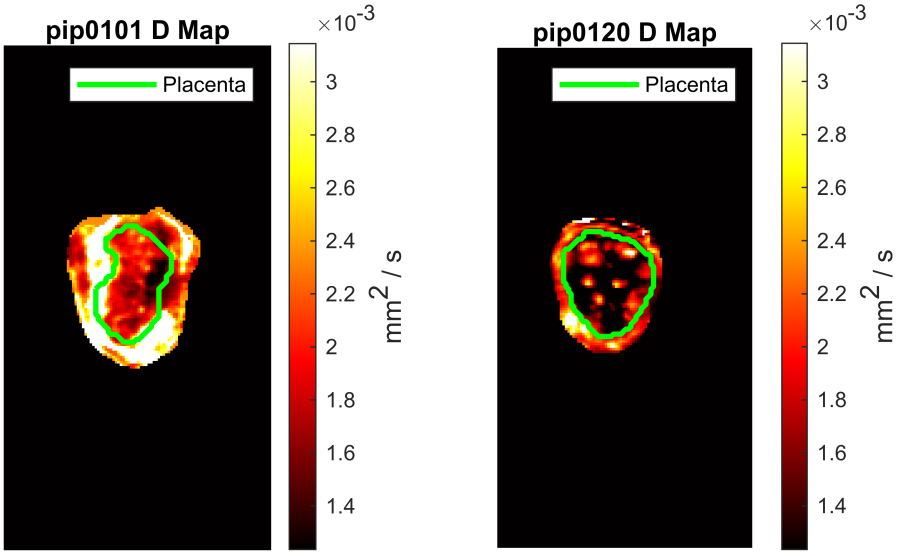



```
figure
x1 = pip0101_D_ADC_map(~isnan(pip0101_D_ADC_map));
x2 = pip0120_D_ADC_map(~isnan(pip0120_D_ADC_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("D paramiter ADC plot");
```

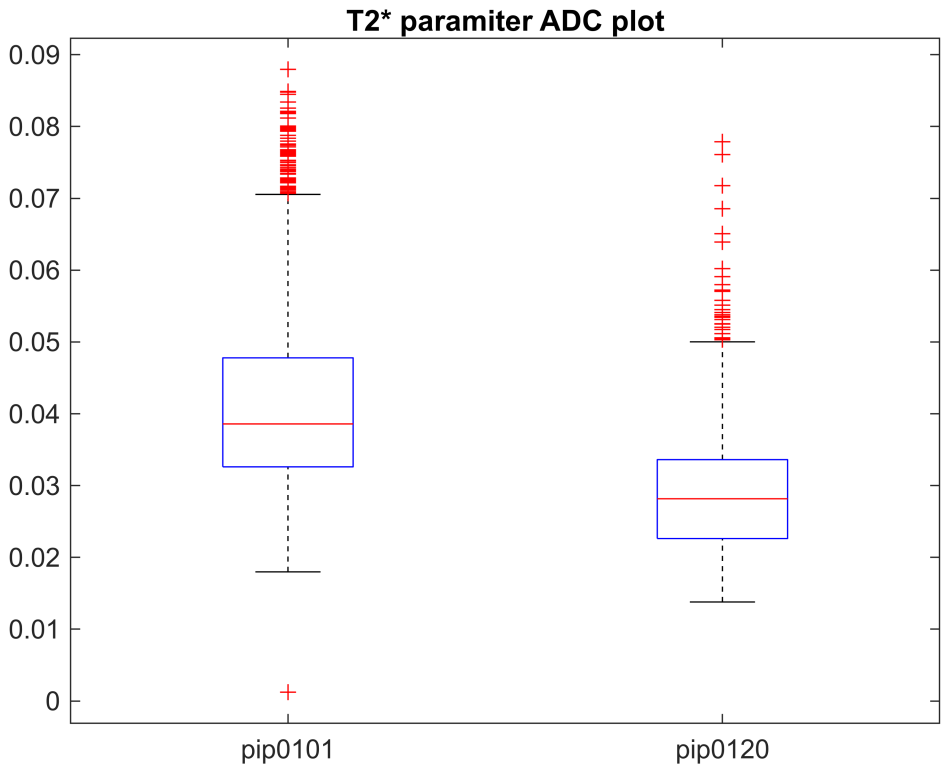



```
range = [quantile(x1,[.25 .75]) quantile(x2,[.25 .75])];
figure
sgtitle('ADC Model D Parameter Maps')
subplot(1,2,1);
imshow(pip0101_D_ADC_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 D Map");
c = colorbar;
c.Label.String = "mm^2 / s";
c.Label.FontSize = 10;
legend("Placenta")
subplot(1,2,2);
imshow(pip0120_D_ADC_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 D Map");
c = colorbar;
c.Label.String = "mm^2 / s";
c.Label.FontSize = 10;
legend("Placenta")
saveas(gcf,"CW3\Figures\ADC_D_maps",'epsc');
```

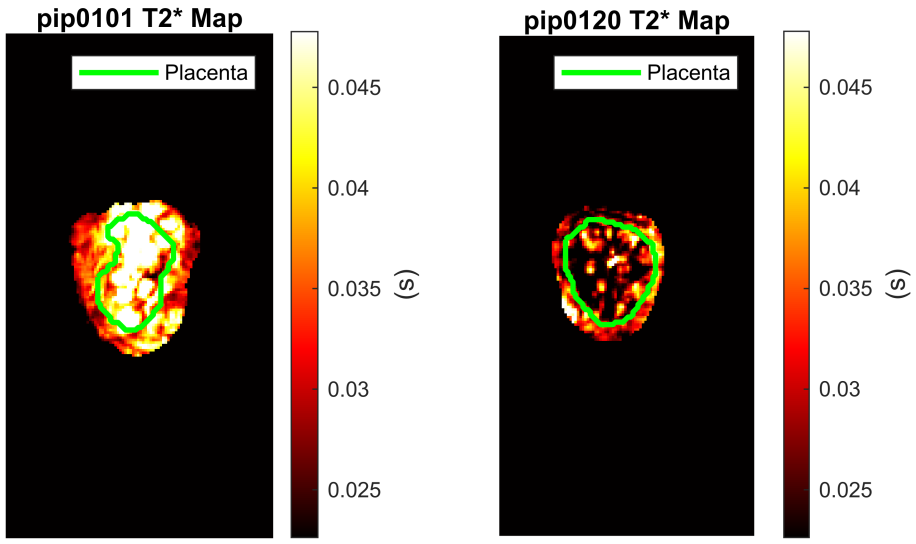
ADC Model D Parameter Maps



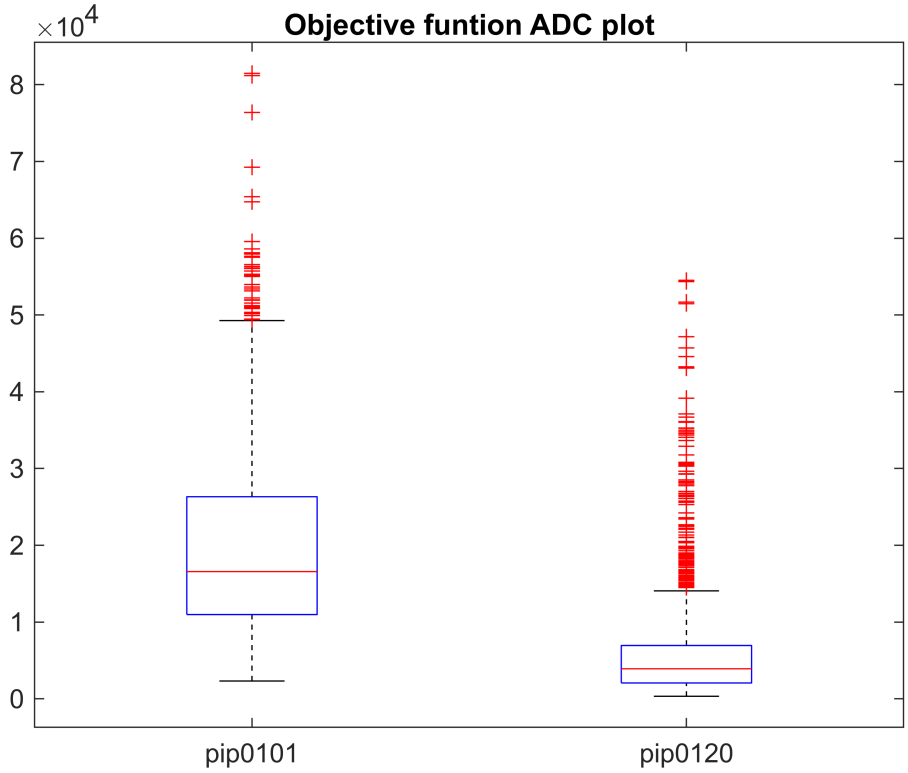

```
figure
x1 = pip0101_T_star_ADC_map(~isnan(pip0101_T_star_ADC_map));
x2 = pip0120_T_star_ADC_map(~isnan(pip0120_T_star_ADC_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("T2* paramiter ADC plot");
```




```
range = [quantile(x1,[.25 .75]) quantile(x2,[.25 .75])];
figure
sgtitle('ADC Model T2* Parameter Maps')
subplot(1,2,1);
imshow(pip0101_T_star_ADC_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 T2* Map");
c = colorbar;
c.Label.String = "(s)";
c.Label.FontSize = 10;
legend("Placenta")
subplot(1,2,2);
imshow(pip0120_T_star_ADC_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 T2* Map");
c = colorbar;
c.Label.String = "(s)";
c.Label.FontSize = 10;
legend("Placenta")
saveas(gcf,"CW3\Figures\ADC_T2_star_maps",'epsc');
```




```
figure
x1 = pip0101_f_values_ADC_map(~isnan(pip0101_f_values_ADC_map));
x2 = pip0120_f_values_ADC_map(~isnan(pip0120_f_values_ADC_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("Objective funtion ADC plot");
```



Task 5 – Fit the combined T2*-Intravoxel incoherent motion (IVIM) model

ROI Parameter Initialisation

```
Avox = squeeze(pip0101_image(100,49,7,:));
x0 = [0,10e-5,0.001,10e-5,0]; % 1:S0, 2:d 3:T2_star 4:Dp 5:f
lower_bounds = [0,10e-5,0.001,10e-5,0];
upper_bounds =[10e5,1,1,1,1];
A = [0,1,0,-1,0]; % Dp > d therefore d + (-Dp) <= 0
b = 0;

mask = double(pip0101_placenta_and_uterine_mask);
mask(mask==0) = NaN;

ROI_mean = squeeze(mean(pip0101_image .* mask,[1,2,3],'omitnan'));

f = @(x)T2_star_IVIM(x,ROI_mean,bvals,echo_times);
options = optimoptions(@fmincon,"Display","iter");

[x0,fval] = fmincon(f,x0,A,b,[],[],lower_bounds,upper_bounds,[],options)
```

```
Your initial point x0 is not between bounds lb and ub; FMINCON
shifted x0 to strictly satisfy the bounds.

                                          First-order      Norm of
 Iter F-count            f(x)  Feasibility   optimality         step
```

```
    0       6    1.612897e+05    0.000e+00    1.285e+03
    1      15    1.385850e+05    0.000e+00    2.379e+04    5.211e+01
    2      21    1.109762e+05    0.000e+00    2.179e+05    6.840e+00
    3      27    1.087028e+05    0.000e+00    2.446e+05    2.602e-01
    4      34    1.056996e+05    0.000e+00    3.710e+05    1.661e+00
    5      40    5.589265e+04    0.000e+00    2.513e+06    8.702e-01
    6      46    5.498661e+04    0.000e+00    1.836e+07    2.372e-01
    7      52    4.920087e+04    0.000e+00    2.122e+07    1.938e+00
    8      61    4.128807e+04    1.333e-03    2.951e+06    8.067e+00
    9      67    3.956094e+04    2.093e-03    2.816e+06    1.600e+00
   10      73    3.574708e+04    2.077e-03    1.049e+06    2.399e+00
   11      79    3.161294e+04    1.908e-03    1.605e+06    7.874e+00
   12      85    3.158703e+04    1.907e-03    1.606e+06    5.152e-02
   13      91    2.512736e+04    0.000e+00    8.200e+06    2.354e+01
   14      97    2.508258e+04    0.000e+00    8.206e+06    8.276e-02
   15     105    1.853606e+04    0.000e+00    8.006e+05    1.751e+01
   16     111    1.640827e+04    0.000e+00    4.494e+05    3.443e+00
   17     117    1.082345e+04    0.000e+00    1.362e+06    3.415e+01
   18     123    8.315832e+03    0.000e+00    1.786e+06    2.814e+01
   19     129    6.740428e+03    0.000e+00    1.082e+06    3.317e+01
   20     136    5.483769e+03    0.000e+00    1.840e+06    3.293e+01
   21     142    5.056127e+03    0.000e+00    1.633e+06    4.551e+00
   22     148    3.641883e+03    0.000e+00    1.241e+06    4.662e+01
   23     155    2.473369e+03    0.000e+00    2.075e+06    4.849e+01
   24     163    1.875005e+03    0.000e+00    1.211e+06    3.946e+01
   25     170    1.284431e+03    0.000e+00    3.100e+06    2.194e+01
   26     177    9.922799e+02    0.000e+00    7.425e+04    3.271e-01
   27     184    8.725080e+02    0.000e+00    1.447e+05    1.204e+01
   28     190    8.506514e+02    0.000e+00    7.648e+04    5.980e+00
   29     196    8.455470e+02    0.000e+00    6.777e+04    6.082e-01
   30     202    8.378727e+02    0.000e+00    1.239e+05    3.239e+00

                                             First-order      Norm of
 Iter F-count            f(x)  Feasibility   optimality         step
   31     208    8.255542e+02    0.000e+00    1.538e+05    7.893e+00
   32     214    8.127033e+02    0.000e+00    1.005e+05    1.253e+01
   33     220    8.102249e+02    0.000e+00    2.264e+04    6.183e+00
   34     226    8.101139e+02    0.000e+00    6.500e+03    7.714e-01
   35     232    8.100792e+02    0.000e+00    3.716e+03    5.821e-01
   36     238    8.100743e+02    0.000e+00    3.941e+03    5.500e-02
   37     244    8.100427e+02    0.000e+00    3.881e+03    1.562e-01
   38     250    8.099020e+02    0.000e+00    8.833e+03    5.185e-01
   39     256    8.096773e+02    0.000e+00    1.487e+04    4.477e-01
   40     262    8.089877e+02    0.000e+00    2.555e+04    7.058e-01
   41     268    8.074294e+02    0.000e+00    3.615e+04    5.257e-01
   42     274    8.037561e+02    0.000e+00    3.217e+04    5.404e-01
   43     280    8.019467e+02    0.000e+00    3.758e+04    3.244e+00
   44     286    8.009591e+02    0.000e+00    7.031e+03    2.774e-01
   45     292    8.008605e+02    0.000e+00    2.086e+03    6.308e-01
   46     298    8.008565e+02    0.000e+00    7.910e+02    1.779e-01
   47     304    8.008562e+02    0.000e+00    6.136e+02    8.059e-04
   48     310    8.008558e+02    0.000e+00    2.004e+02    3.601e-03
   49     316    8.008558e+02    0.000e+00    4.787e+01    6.939e-04
   50     322    8.008558e+02    0.000e+00    2.753e+00    5.109e-05
   51     328    8.008557e+02    0.000e+00    1.048e+01    1.532e-02
   52     340    8.008557e+02    0.000e+00    2.047e-02    4.777e-07
   53     346    8.008557e+02    0.000e+00    1.186e+00    3.750e-03

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.
```

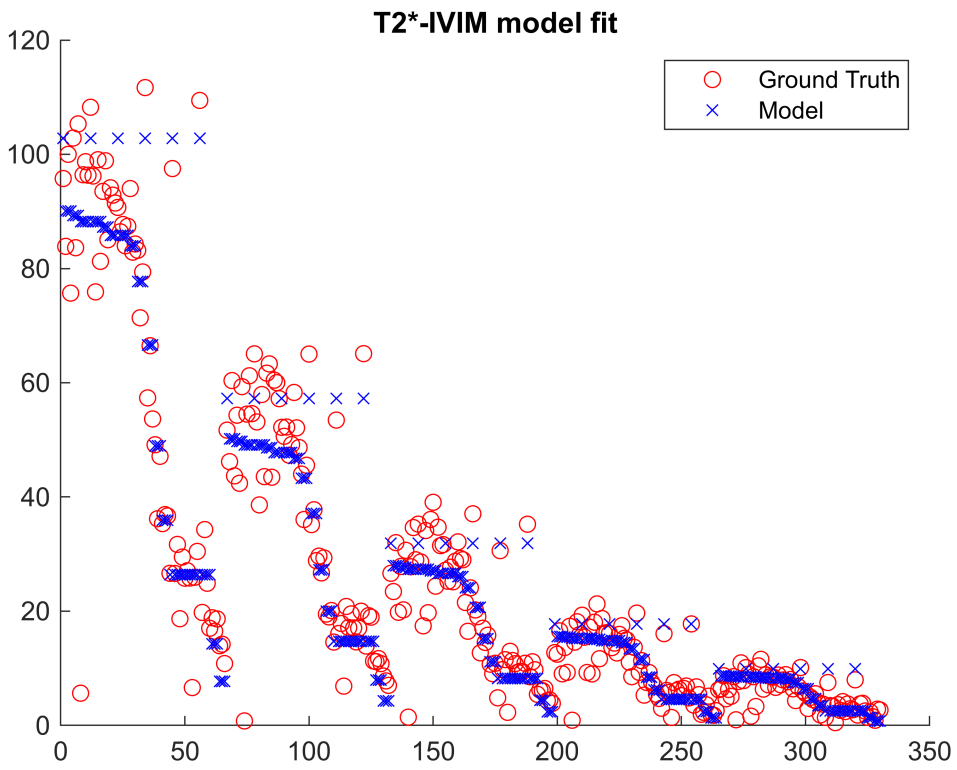
```
<stopping criteria details>
x0 = 1×5
  427.8989    0.0018    0.0442    0.0662    0.2999
fval = 800.8557
```

```
f = @(x)T2_star_IVIM(x,Avox,bvals,echo_times);
[x,fval] = fmincon(f,x0,A,b,[],[],lower_bounds,upper_bounds,[],options)
```

```
                                         First-order      Norm of
 Iter F-count            f(x)  Feasibility  optimality         step
    0       6    1.072721e+05    0.000e+00    1.039e+07
    1      18    3.160173e+04    0.000e+00    1.151e+05    2.641e-02
    2      27    3.129117e+04    0.000e+00    3.895e+06    4.453e-01
    3      36    2.913842e+04    0.000e+00    8.733e+06    5.317e+01
    4      43    2.496027e+04    0.000e+00    5.416e+06    2.923e+01
    5      50    2.187462e+04    0.000e+00    1.670e+07    5.609e+01
    6      57    2.066253e+04    0.000e+00    6.238e+06    1.048e+01
    7      65    2.060760e+04    0.000e+00    3.814e+06    1.152e+01
    8      73    1.998410e+04    0.000e+00    4.252e+06    5.287e+01
    9      82    1.912439e+04    0.000e+00    5.413e+06    1.963e+01
   10      88    1.851420e+04    0.000e+00    2.961e+05    4.350e+00
   11      97    1.848143e+04    0.000e+00    1.589e+06    1.476e+01
   12     105    1.842231e+04    0.000e+00    1.581e+06    7.178e+00
   13     111    1.837077e+04    0.000e+00    2.095e+05    2.535e+00
   14     117    1.835837e+04    0.000e+00    2.031e+04    1.628e-01
   15     123    1.829991e+04    0.000e+00    6.543e+05    1.724e+00
   16     129    1.824371e+04    0.000e+00    8.264e+05    9.548e-01
   17     135    1.818387e+04    0.000e+00    5.833e+05    1.462e+00
   18     141    1.813489e+04    0.000e+00    1.675e+05    4.143e+00
   19     147    1.811239e+04    0.000e+00    1.136e+05    3.703e+00
   20     153    1.810221e+04    0.000e+00    2.196e+05    1.803e+00
   21     159    1.809236e+04    0.000e+00    2.325e+05    6.439e-01
   22     165    1.808149e+04    0.000e+00    1.524e+05    8.304e-01
   23     171    1.807450e+04    0.000e+00    3.874e+04    1.787e+00
   24     177    1.807221e+04    0.000e+00    2.409e+04    1.156e+00
   25     183    1.807210e+04    0.000e+00    2.587e+04    3.436e-02
   26     189    1.807209e+04    0.000e+00    1.250e+04    1.597e-01
   27     195    1.807206e+04    0.000e+00    7.587e+02    1.538e-01
   28     201    1.807206e+04    0.000e+00    3.072e+02    3.902e-03
   29     207    1.807206e+04    0.000e+00    5.131e+01    1.061e-03
   30     222    1.807206e+04    0.000e+00    3.642e-02    3.654e-09

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than
the value of the step size tolerance and constraints are
satisfied to within the value of the constraint tolerance.

<stopping criteria details>
x = 1×5
  365.1751    0.0015    0.0615    0.9999    0.1178
fval = 1.8072e+04
```

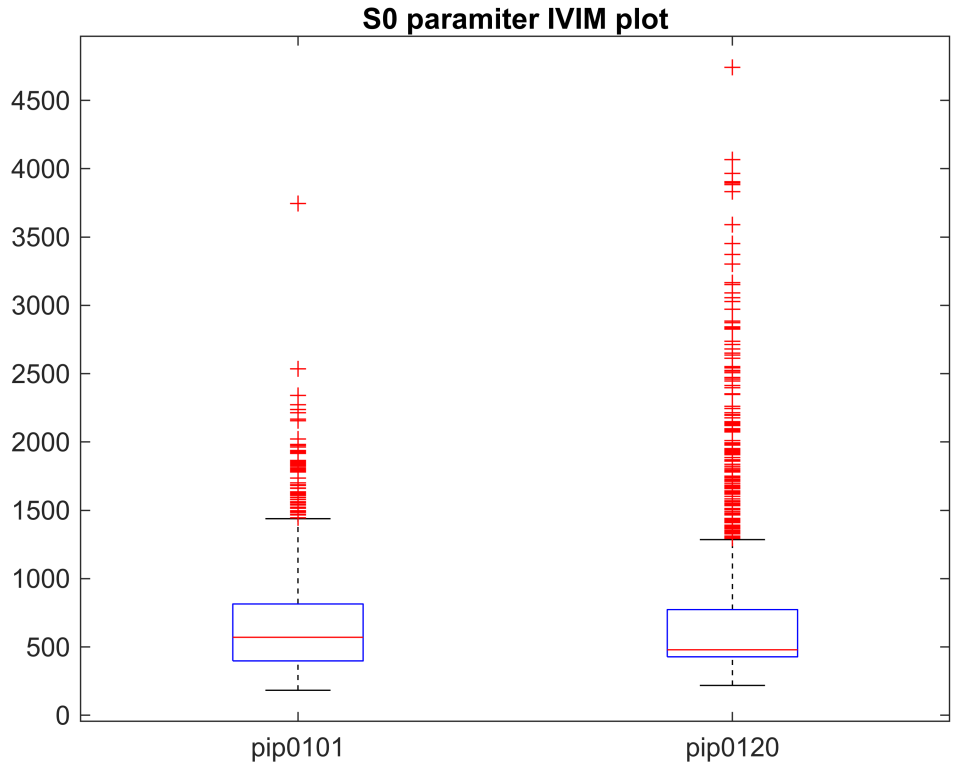
```
xs = 1:length(Avox);
model = x(1) * exp(-echo_times/x(3)) .* (x(5) * exp(-bvals*x(4)) + (1-x(5)) * exp(-bvals * x(2)
figure("Name","Single voxel T2_star_IVIM fit");
scatter(xs,Avox,"o","CData",[1,0,0])
hold on
scatter(xs,model,"x","CData",[0,0,1]);
title("T2*-IVIM model fit");
```

```
legend(["Ground Truth","Model"]);
hold off
```

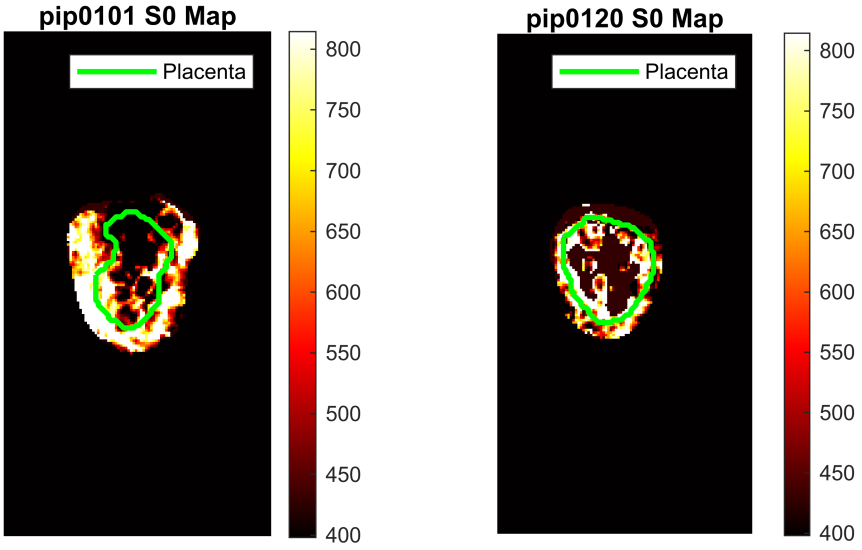



```
mask_shape = size(pip0101_placenta_and_uterine_mask(:,:,7));
pip0101_S0_IVIM_map = zeros(mask_shape);
pip0101_D_IVIM_map = zeros(mask_shape);
pip0101_T_star_IVIM_map = zeros(mask_shape);
pip0101_Dp_IVIM_map = zeros(mask_shape);
pip0101_f_IVIM_map = zeros(mask_shape);
pip0101_f_values_IVIM_map = zeros(mask_shape);
options = optimoptions(@fmincon,"Display","off");
for i = 1:mask_shape(1)
    for j = 1:mask_shape(2)
        if pip0101_placenta_and_uterine_mask(i,j,7) == 1
            Avox = squeeze(pip0101_image(i,j,7,:));
            f = @(x)T2_star_IVIM(x,Avox,bvals,echo_times);
            [x,fval] = fmincon(f,x0,A,b,[],[],lower_bounds,upper_bounds,[],options);
            pip0101_S0_IVIM_map(i,j) = x(1);
            pip0101_D_IVIM_map(i,j) = x(2);
            pip0101_T_star_IVIM_map(i,j) = x(3);
            pip0101_Dp_IVIM_map(i,j) = x(4);
            pip0101_f_IVIM_map(i,j) = x(5);
            pip0101_f_values_IVIM_map(i,j) = fval;
        else
            pip0101_S0_IVIM_map(i,j) = NaN;
            pip0101_D_IVIM_map(i,j) = NaN;
```

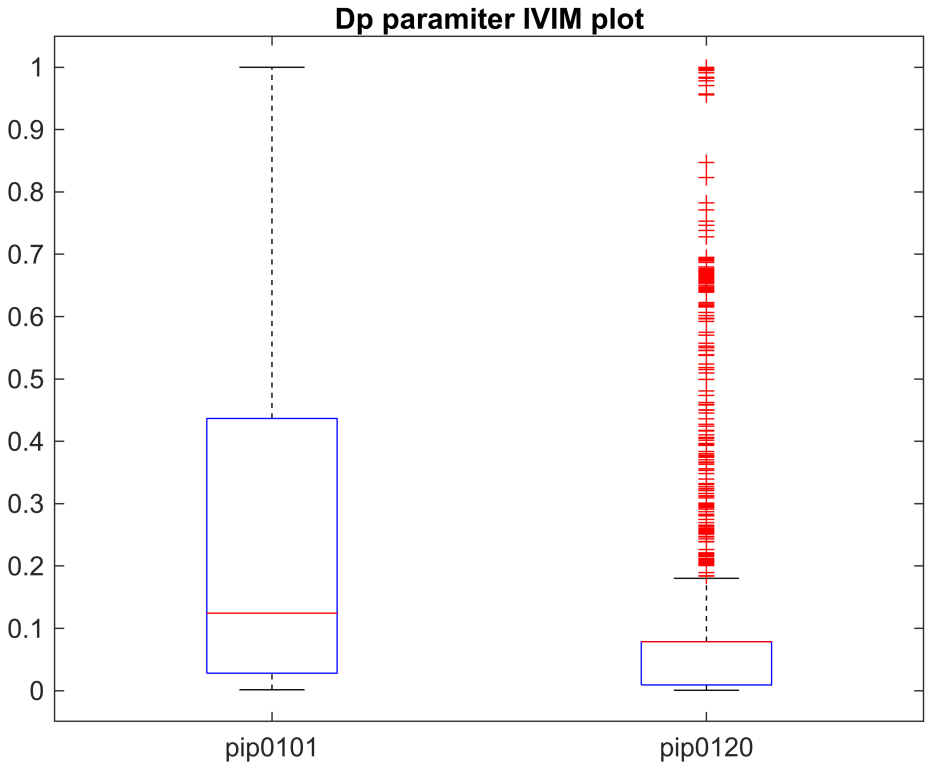
```
            pip0101_T_star_IVIM_map(i,j) = NaN;
            pip0101_Dp_IVIM_map(i,j) = NaN;
            pip0101_f_IVIM_map(i,j) = NaN;
            pip0101_f_values_IVIM_map(i,j) = NaN;

        end
    end
end
mask_shape = size(pip0120_placenta_and_uterine_mask(:,:,7));
pip0120_S0_IVIM_map = zeros(mask_shape);
pip0120_D_IVIM_map = zeros(mask_shape);
pip0120_T_star_IVIM_map = zeros(mask_shape);
pip0120_Dp_IVIM_map = zeros(mask_shape);
pip0120_f_IVIM_map = zeros(mask_shape);
pip0120_f_values_IVIM_map = zeros(mask_shape);
for i = 1:mask_shape(1)
    for j = 1:mask_shape(2)
        if pip0120_placenta_and_uterine_mask(i,j,7) == 1
            Avox = squeeze(pip0120_image(i,j,7,:));
            f = @(x)T2_star_IVIM(x,Avox,bvals,echo_times);
            [x,fval] = fmincon(f,x0,A,b,[],[],lower_bounds,upper_bounds,[],options);
            pip0120_S0_IVIM_map(i,j) = x(1);
            pip0120_D_IVIM_map(i,j) = x(2);
            pip0120_T_star_IVIM_map(i,j) = x(3);
            pip0120_Dp_IVIM_map(i,j) = x(4);
            pip0120_f_IVIM_map(i,j) = x(5);
            pip0120_f_values_IVIM_map(i,j) = fval;
        else
            pip0120_S0_IVIM_map(i,j) = NaN;
            pip0120_D_IVIM_map(i,j) = NaN;
            pip0120_T_star_IVIM_map(i,j) = NaN;
            pip0120_Dp_IVIM_map(i,j) = NaN;
            pip0120_f_IVIM_map(i,j) = NaN;
            pip0120_f_values_IVIM_map(i,j) = NaN;

        end
    end
end
figure
x1 = pip0101_S0_IVIM_map(~isnan(pip0101_S0_IVIM_map));
x2 = pip0120_S0_IVIM_map(~isnan(pip0120_S0_IVIM_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("S0 paramiter IVIM plot");
```



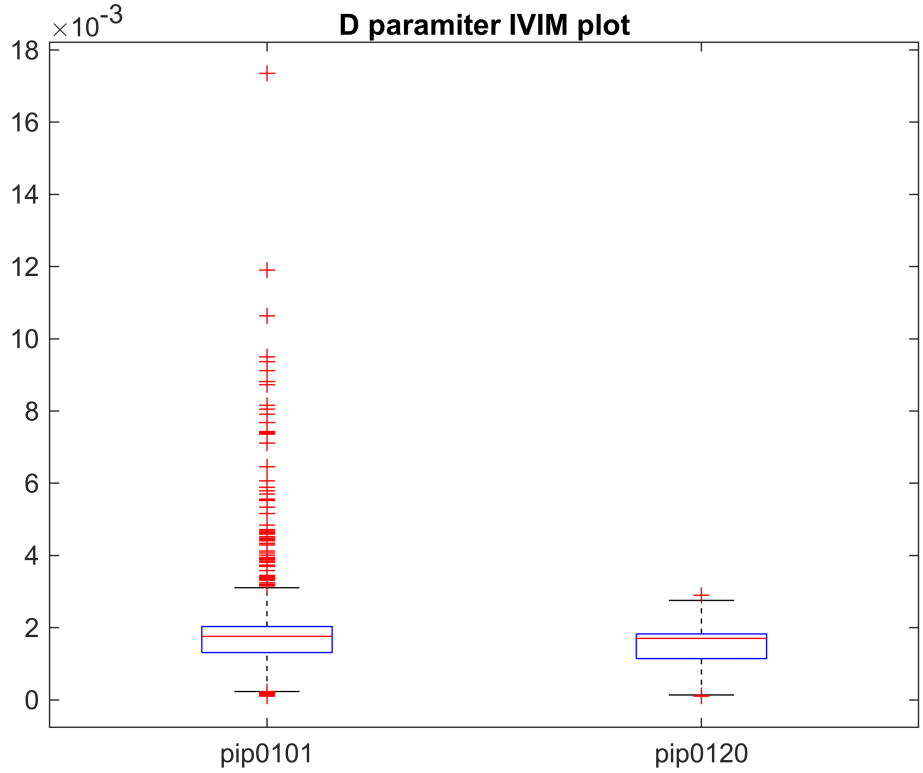

```
range = [quantile(x1,[.25 .75]) quantile(x2,[.25 .75])];
figure
subplot(1,2,1);
imshow(pip0101_S0_IVIM_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 S0 Map");
colorbar;
legend("Placenta")
subplot(1,2,2);
imshow(pip0120_S0_IVIM_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 S0 Map");
colorbar;
legend("Placenta")
saveas(gcf,"CW3\Figures\IVIM_S0_maps",'epsc');
```




```
figure
dp_x1 = pip0101_Dp_IVIM_map(~isnan(pip0101_Dp_IVIM_map));
dp_x2 = pip0120_Dp_IVIM_map(~isnan(pip0120_Dp_IVIM_map));
x = [dp_x1;dp_x2];
g = [zeros(length(dp_x1),1); ones(length(dp_x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("Dp paramiter IVIM plot");
```

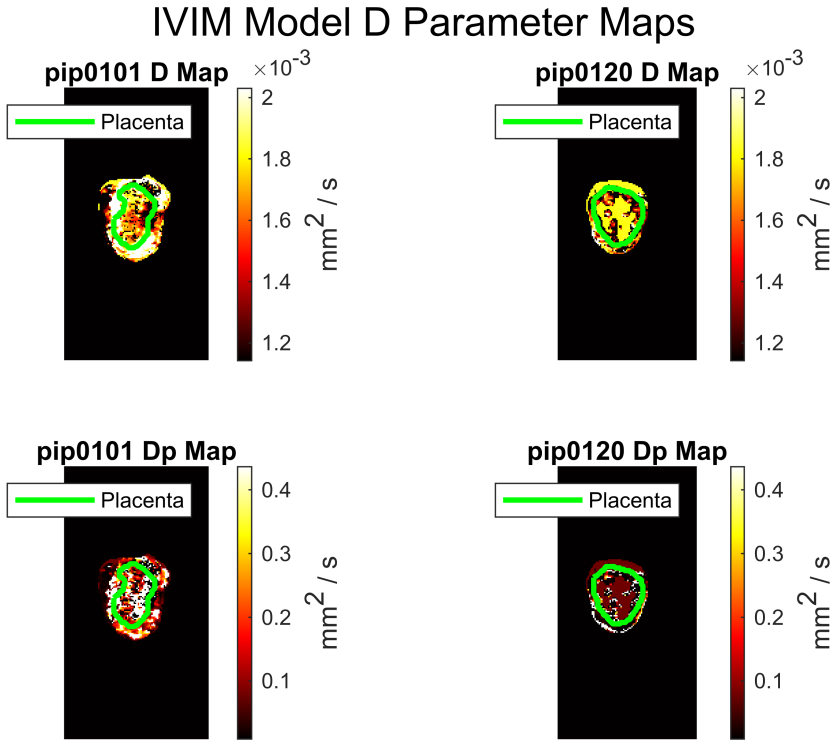



```
figure
d_x1 = pip0101_D_IVIM_map(~isnan(pip0101_D_IVIM_map));
d_x2 = pip0120_D_IVIM_map(~isnan(pip0120_D_IVIM_map));
x = [d_x1;d_x2];
g = [zeros(length(d_x1),1); ones(length(d_x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("D paramiter IVIM plot");
```



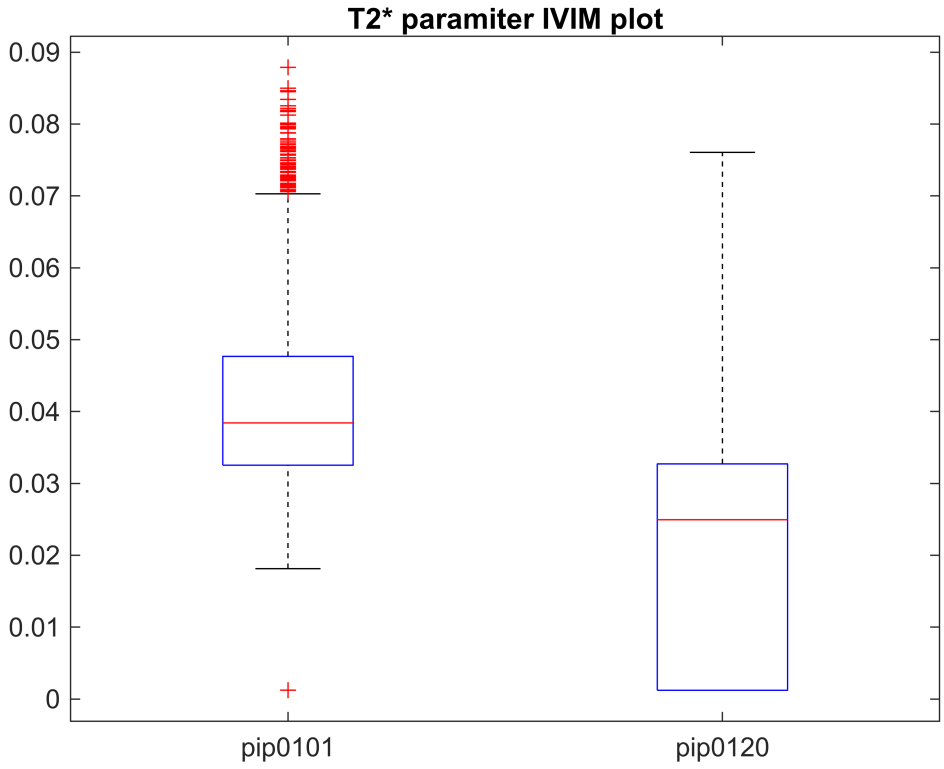

```
d_range = [quantile(d_x1,[.25 .75]) quantile(d_x2,[.25 .75])];
dp_range = [quantile(dp_x1,[.25 .75]) quantile(dp_x2,[.25 .75])];
figure
sgtitle('IVIM Model D Parameter Maps')
subplot(2,2,1);
imshow(pip0101_D_IVIM_map,[min(d_range),max(d_range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 D Map");
c = colorbar;
c.Label.String = "mm^2 / s";
c.Label.FontSize = 10;
legend("Placenta")
subplot(2,2,2);
imshow(pip0120_D_IVIM_map,[min(d_range),max(d_range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 D Map");
c = colorbar;
c.Label.String = "mm^2 / s";
c.Label.FontSize = 10;
legend("Placenta")
subplot(2,2,3);
imshow(pip0101_Dp_IVIM_map,[min(dp_range),max(dp_range)],colormap=hot);
```

```
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 Dp Map");
c = colorbar;
c.Label.String = "mm^2 / s";
c.Label.FontSize = 10;
legend("Placenta")
subplot(2,2,4);
imshow(pip0120_Dp_IVIM_map,[min(dp_range),max(dp_range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 Dp Map");
c = colorbar;
c.Label.String = "mm^2 / s";
c.Label.FontSize = 10;
legend("Placenta")
saveas(gcf,"CW3\Figures\IVIM_D_and_Dp_maps",'epsc');
```

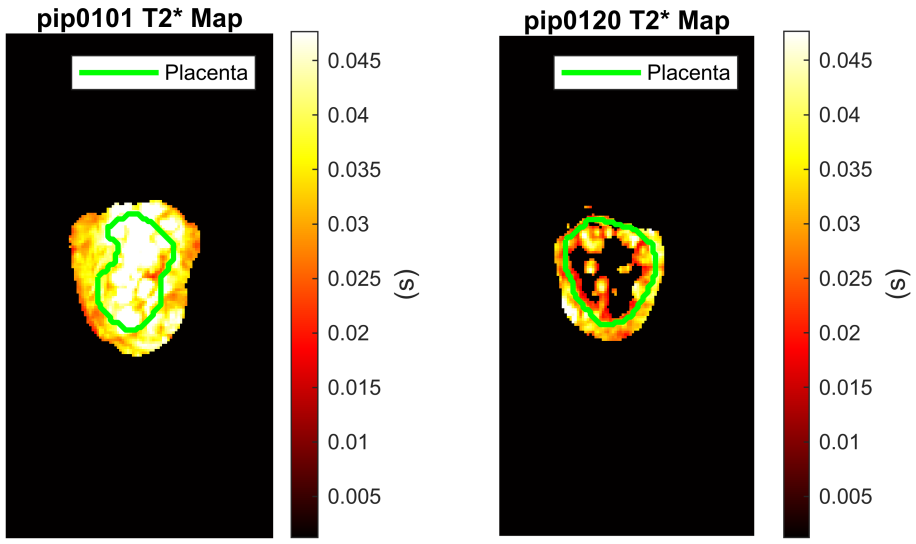



```
figure
x1 = pip0101_T_star_IVIM_map(~isnan(pip0101_T_star_IVIM_map));
x2 = pip0120_T_star_IVIM_map(~isnan(pip0120_T_star_IVIM_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
```

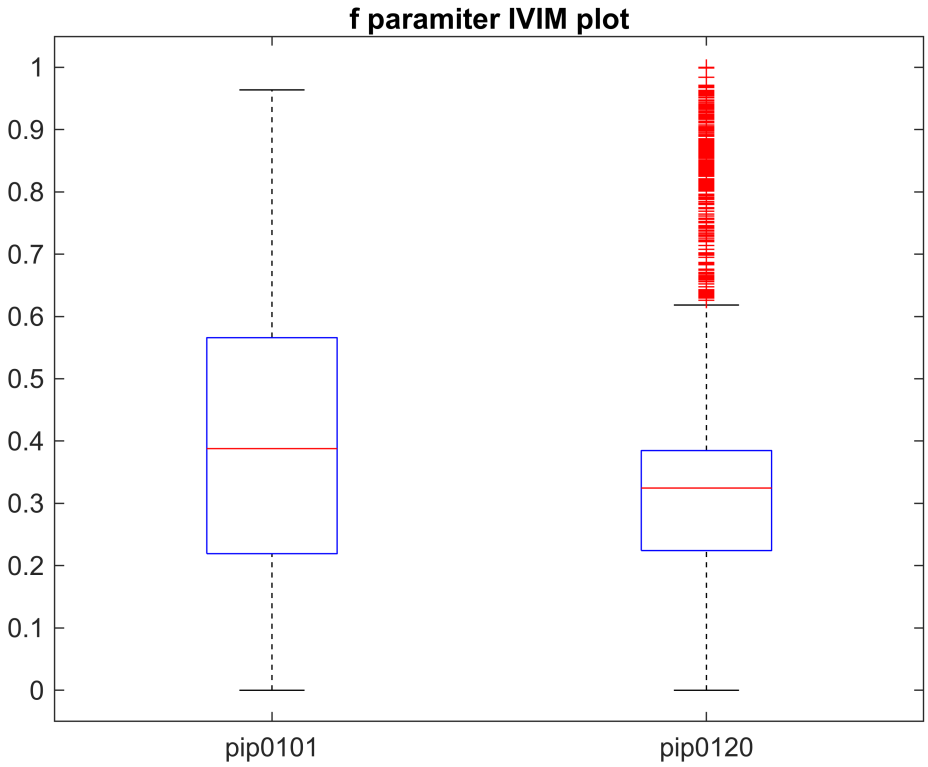
```
title("T2* paramiter IVIM plot");
```



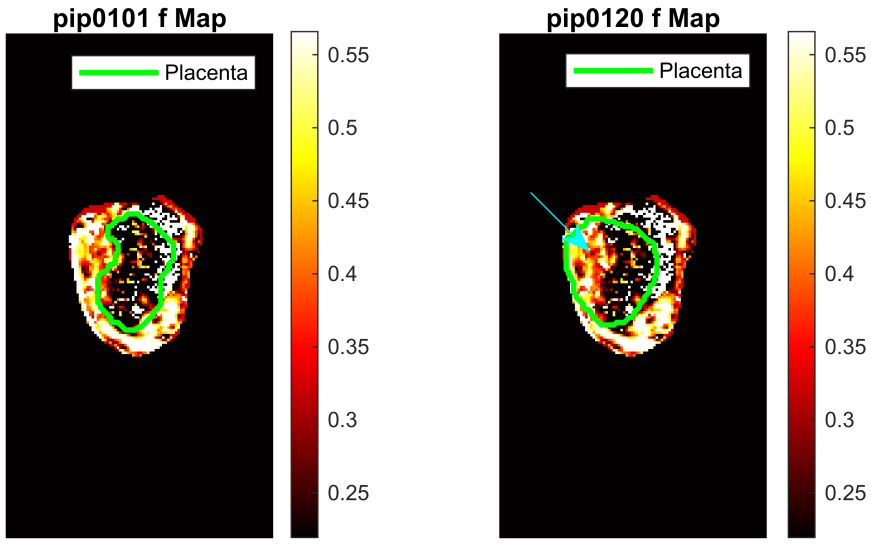

```
range = [quantile(x1,[.25 .75]) quantile(x2,[.25 .75])];
figure
sgtitle('IVIM Model T2* Parameter Maps')
subplot(1,2,1);
imshow(pip0101_T_star_IVIM_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 T2* Map");
c = colorbar;
c.Label.String = "(s)";
c.Label.FontSize = 10;
legend("Placenta")
subplot(1,2,2);
imshow(pip0120_T_star_IVIM_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 T2* Map");
c = colorbar;
c.Label.String = "(s)";
c.Label.FontSize = 10;
legend("Placenta")
saveas(gcf,"CW3\Figures\IVIM_T2_star_maps",'epsc');
```



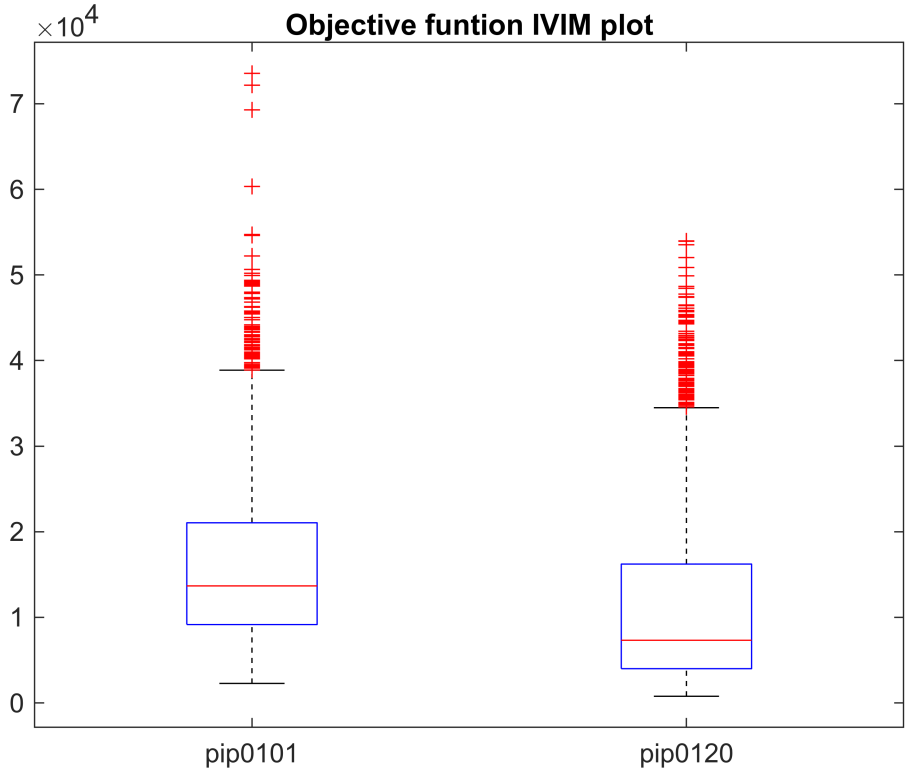

```
figure
x1 = pip0101_f_IVIM_map(~isnan(pip0101_f_IVIM_map));
x2 = pip0120_f_IVIM_map(~isnan(pip0120_f_IVIM_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("f paramiter IVIM plot");
```




```
range = [quantile(x1,[.25 .75]) quantile(x2,[.25 .75])];
figure
sgtitle('IVIM Model f Parameter Maps')
subplot(1,2,1);
imshow(pip0101_f_IVIM_map,[min(range),max(range)],colormap=hot);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 f Map");
colorbar;
legend("Placenta")
subplot(1,2,2);
imshow(pip0101_f_IVIM_map,[min(range),max(range)],colormap=hot);
ar = annotation("arrow", [0.5982 0.65], [0.6262 0.5571]);
ar.Color = [0,1,1];
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 f Map");
colorbar;
legend("Placenta")
saveas(gcf,"CW3\Figures\IVIM_f_maps",'epsc');
```




```
figure
x1 = pip0101_f_values_IVIM_map(~isnan(pip0101_f_values_IVIM_map));
x2 = pip0120_f_values_IVIM_map(~isnan(pip0120_f_values_IVIM_map));
x = [x1;x2];
g = [zeros(length(x1),1); ones(length(x2),1)];
boxplot(x,g,'Labels',["pip0101","pip0120"])
title("Objective funtion IVIM plot");
```



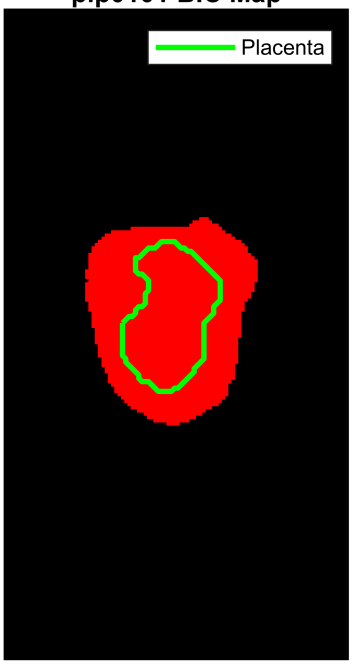
Task 6 – Model selection with BIC

```
n = 330;
ADC_paramiter_number = 3;
IVIM_paramiter_number = 5;
pip0101_ADC_BIC_MAP = zeros(size(pip0101_f_values_ADC_map));
pip0101_IVIM_BIC_MAP = zeros(size(pip0101_f_values_IVIM_map));
pip0120_ADC_BIC_MAP = zeros(size(pip0120_f_values_ADC_map));
pip0120_IVIM_BIC_MAP = zeros(size(pip0120_f_values_IVIM_map));

pip0101_BIC_MAP = zeros(200,106,3);
pip0120_BIC_MAP = zeros(200,102, 3);

for i = 1:pip0101_size(1)
    for j = 1:pip0101_size(2)
        ADC_L = pip0101_f_values_ADC_map(i,j);
        IVIM_L = pip0101_f_values_IVIM_map(i,j);
        if ~isnan(ADC_L) && ~isnan(IVIM_L)
            ADC_BIC = BIC(ADC_paramiter_number,n,ADC_L);
            IVIM_BIC = BIC(IVIM_paramiter_number,n,IVIM_L);
            if ADC_BIC < IVIM_BIC
                pip0101_BIC_MAP(i,j,:) = [1,0,0];
            else
                pip0101_BIC_MAP(i,j,:) = [0,0,1];
            end
```

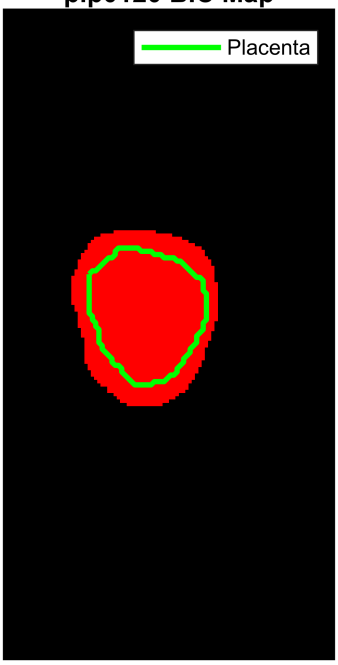
```
        end
    end
end

for i = 1:pip0120_size(1)
    for j = 1:pip0120_size(2)
        ADC_L = pip0120_f_values_ADC_map(i,j);
        IVIM_L = pip0120_f_values_IVIM_map(i,j);
        if ~isnan(ADC_L) && ~isnan(IVIM_L)
            ADC_BIC = BIC(ADC_paramiter_number,n,ADC_L);
            IVIM_BIC = BIC(IVIM_paramiter_number,n,IVIM_L);
            if ADC_BIC < IVIM_BIC
                pip0120_BIC_MAP(i,j,:) = [1,0,0];
            else
                pip0120_BIC_MAP(i,j,:) = [0,0,1];
            end
        end
    end
end
figure
sgtitle('BIC Maps')
subplot(1,2,1);
imshow(pip0101_BIC_MAP);
hold on;
plot(B1{1}(:,2), B1{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0101 BIC Map");
legend("Placenta")
subplot(1,2,2);
imshow(pip0120_BIC_MAP);
hold on;
plot(B2{1}(:,2), B2{1}(:,1), 'g', 'LineWidth', 2);
hold off;
title("pip0120 BIC Map");
legend("Placenta")
saveas(gcf,"CW3\Figures\BIC_maps",'epsc');
```

BIC Maps

pip0101 BIC Map

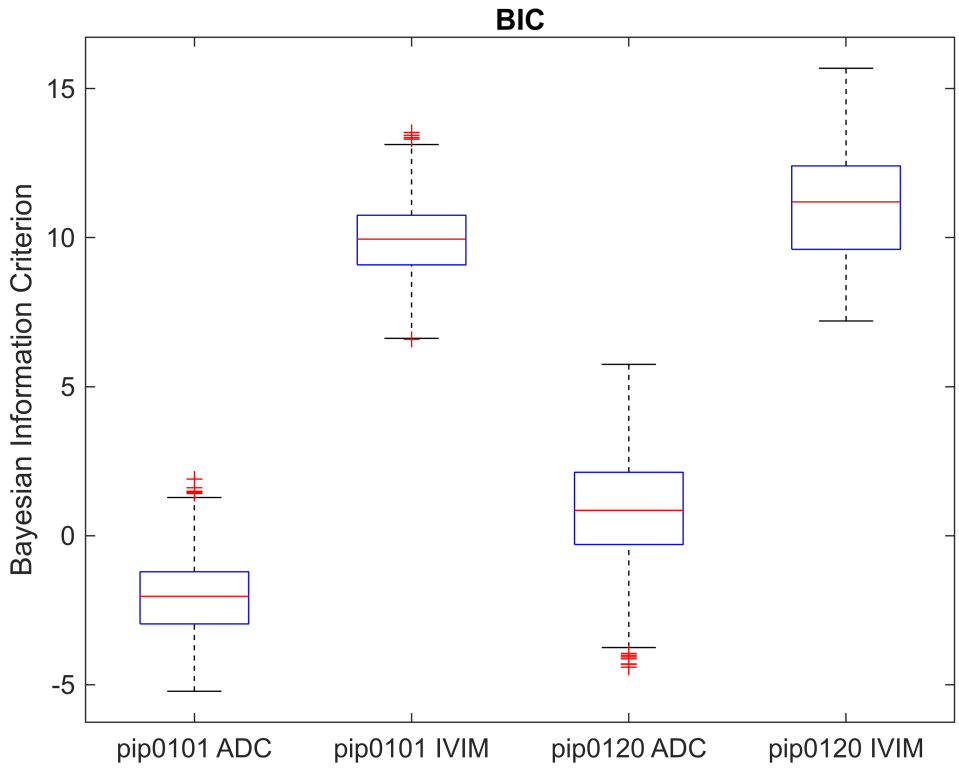


pip0120 BIC Map




```
for i = 1:pip0101_size(1)
    for j = 1:pip0101_size(2)
        L = pip0101_f_values_ADC_map(i,j);
        if  ~isnan(L)
            pip0101_ADC_BIC_MAP(i,j) = BIC(ADC_paramiter_number,n,L);
        else
            pip0101_ADC_BIC_MAP(i,j) = NaN;
        end
        L = pip0101_f_values_IVIM_map(i,j);
        if ~isnan(L)
            pip0101_IVIM_BIC_MAP(i,j) = BIC(IVIM_paramiter_number,n,L);
        else
            pip0101_IVIM_BIC_MAP(i,j) = NaN;
        end
    end
end

for i = 1:pip0120_size(1)
    for j = 1:pip0120_size(2)
        L = pip0120_f_values_ADC_map(i,j);
        if  ~isnan(L)
            pip0120_ADC_BIC_MAP(i,j) = BIC(ADC_paramiter_number,n,L);
        else
            pip0120_ADC_BIC_MAP(i,j) = NaN;
        end
        L = pip0120_f_values_IVIM_map(i,j);
```

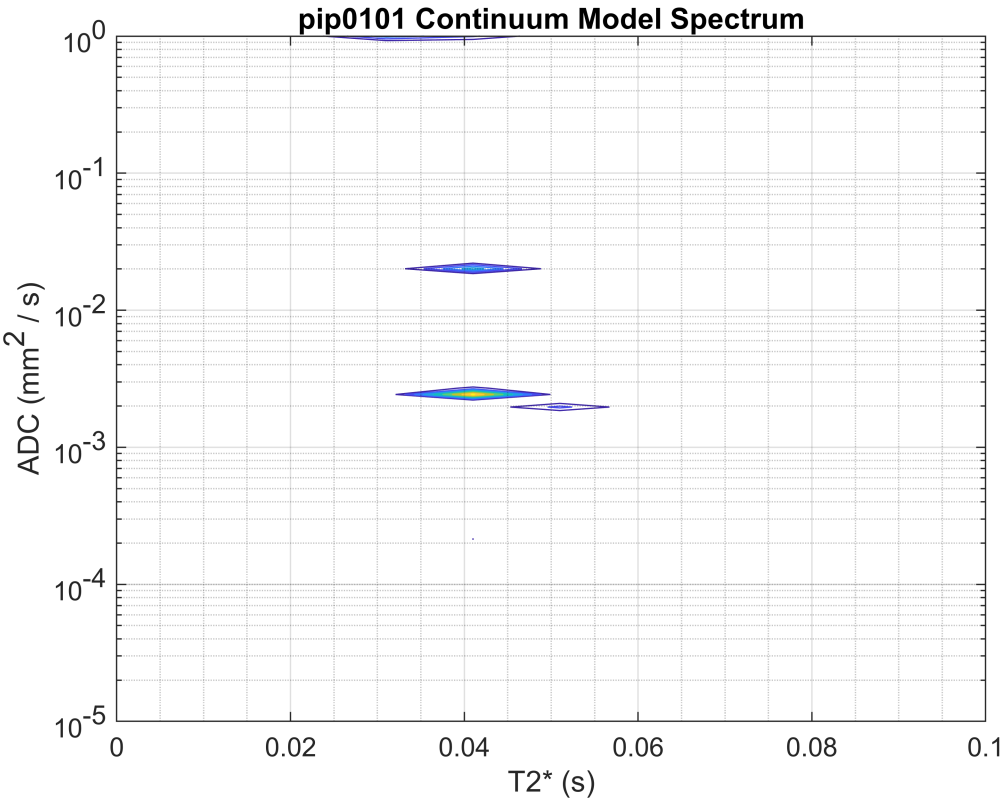
```
        if ~isnan(L)
            pip0120_IVIM_BIC_MAP(i,j) = BIC(IVIM_paramiter_number,n,L);
        else
            pip0120_IVIM_BIC_MAP(i,j) = NaN;
        end
    end
end

figure
x1 = pip0101_ADC_BIC_MAP(~isnan(pip0101_ADC_BIC_MAP));
x2 = pip0101_IVIM_BIC_MAP(~isnan(pip0101_IVIM_BIC_MAP));
x3 = pip0120_ADC_BIC_MAP(~isnan(pip0120_ADC_BIC_MAP));
x4 = pip0120_IVIM_BIC_MAP(~isnan(pip0120_IVIM_BIC_MAP));
x = [x1;x2;x3;x4];
g = [zeros(length(x1),1); ones(length(x2),1); 2* ones(length(x3),1); 3 * ones(length(x4),1)];
boxplot(x,g,'Labels',["pip0101 ADC","pip0101 IVIM","pip0120 ADC","pip0120 IVIM"])
ylabel("Bayesian Information Criterion")
title("BIC");
saveas(gcf,"CW3\Figures\BIC_box_plots",'epsc');
```



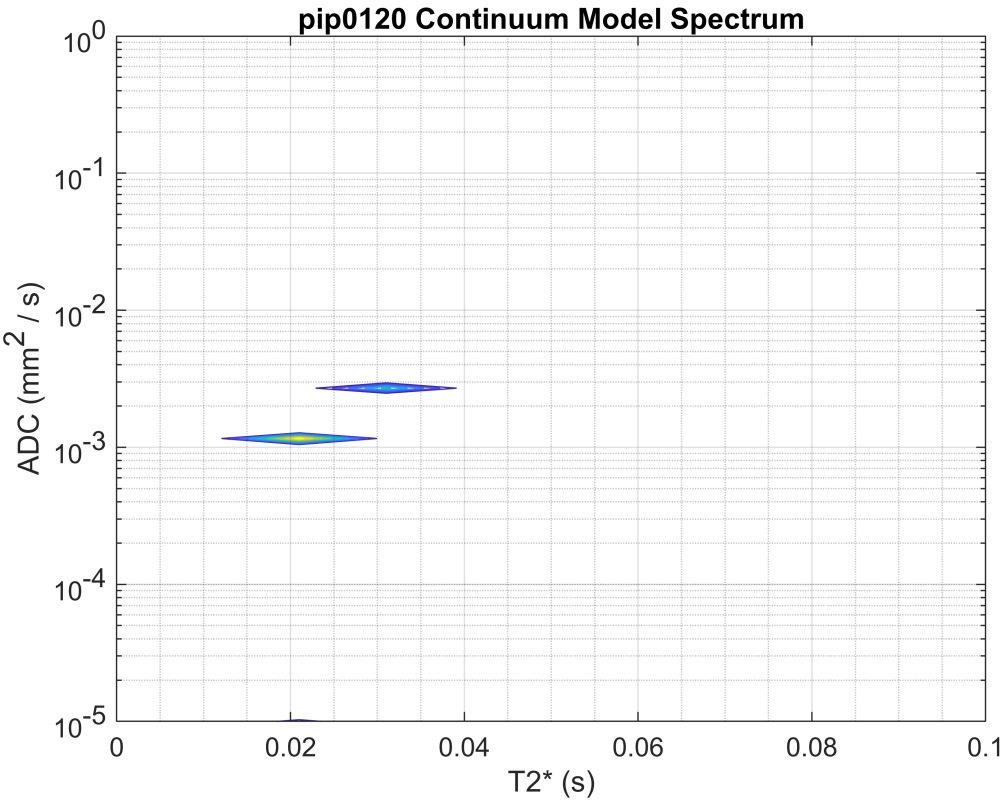
Task 7 – Continuum modelling

```
slice1 = squeeze(pip0101_image(:,:,7,:));
slice2 = squeeze(pip0120_image(:,:,7,:));
t2 = 0.001:0.01:1.1;
N_t2 = length(t2);
d = logspace(-5,0,110);
```

```
N_d = length(d);
K = zeros(330,N_d * N_t2);
k = 1;

for i = 1:N_t2
    for j = 1:N_d
        K(:,k) = exp(-echo_times/t2(i)) .* exp(-bvals * d(j));
        k = k + 1;
    end
end

mask1 = double(pip0101_placenta_and_uterine_mask);
mask1(mask1==0) = NaN;

mask2 = double(pip0120_placenta_and_uterine_mask);
mask2(mask1==0) = NaN;


S1 = squeeze(mean(pip0101_image .* double(mask1),[1,2,3],'omitnan')); %Length Ns
S2 = squeeze(mean(pip0120_image .* double(mask2),[1,2,3],'omitnan')); %Length Ns


F1 = lsqnonneg(K,S1);
F1 = reshape(F1,N_d,N_t2);
F2 = lsqnonneg(K,S2);
F2 = reshape(F2,N_d,N_t2);

figure
contour(t2,d,F1)
title("pip0101 Continuum Model Spectrum")
set(gca,'Yscale','log')
xlim([0 0.1])
ylabel("ADC (mm^2 / s)")
xlabel("T2* (s)")
grid on
grid minor
saveas(gcf,"CW3\Figures\pip0101_continuum_spectrum",'epsc');
```




```
figure
contour(t2,d,F2)
title("pip0120 Continuum Model Spectrum")
set(gca,'Yscale','log')
xlim([0 0.1])
ylabel("ADC (mm^2 / s)")
xlabel("T2* (s)")
grid on
grid minor
saveas(gcf,"CW3\Figures\pip0120_continuum_spectrum",'epsc');
```


pip0120 Continuum Model Spectrum
ADC (mm2 / s)
T2* (s)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0
0.02
0.04
0.06
0.08
0.1