

Effects of electrode configuration and contact impedance on activation function and surface current density

July 9, 2014

Simulations were performed for different electrode configurations to see how the magnitude and the penetration of the activation function and the surface current density depend on the electrode shapes and their relative positions. A three layer model [] for the body was used -

- Layer 1 - Skin, thickness 5 mm and conductivity 0.45 S/m
- Layer 2 - Fat, thickness 7 mm and conductivity 0.04 S/m
- Layer 3 - Muscle, thickness 50 mm and conductivity 0.45 S/m

The thickness of the muscle layer was infinite in case of concentric electrodes where integral equation approach was used. For rest of the simulations, EIDORS [] was used to create the FEM model and find the activation function and surface current density. Due to the finite size of the FEM model, the results very deep in the muscle might be unreliable.

The activation function is the second derivative of the potential along the direction of the nerve []. In case of concentric electrodes the activation function in radial direction was evaluated due to the cylindrical symmetry. In all other cases, the derivative along x-direction was used (where x-axis is usually the line joining the centres of the two electrodes). The potential was smoothed using a smoothing spline allowing for max 2% relative error where FEM was used (this leads to slight reduction of the magnitude of the activation function). Then the activation function was calculated using finite differences. In case of concentric electrodes, finite difference was taken directly.

For each configuration the following plots were generated:

- Activation function as a function of x was calculated at 20 equally spaced depths (at $y=0$ i.e. directly under the line joining the centres of the electrodes).
- 3d plot of activation function at depth of 15 mm (in muscle)
- Surface current density along the x-axis

- 3d plot of surface current density
- Activation function as a function of depth directly underneath the centre of the electrode (the active electrode in case of unsymmetrical configurations)
- 3d plot of activation function at depth of 15 mm (in muscle) with negative portion made zero for clarity

The complete electrode model was used and the current density under the electrode was calculated as $\frac{V_l - \phi(r, \theta, 0)}{Z_l}$ where V_l is the electrode voltage and Z_l is the contact impedance (Ωm^2). 3 distinct values of the contact impedance were used for most of the configurations. From the range of electrode gel conductivity - 1 Ωm to 10 $k\Omega m$ and assuming thickness of gel as 1 mm we can get a range for the contact impedance. Also from [], the average value of impedance in Ω is 800 Ω . As the areas of the electrodes considered is of the order of 10 cm^2 , the average value for contact impedance is nearly 1 Ωm^2 . To find out the effect of contact impedance, three values were chosen - 1 Ωm^2 , 0.01 Ωm^2 and 100 Ωm^2 .

Wherever possible the same areas were chosen for the electrodes in different configurations to make comparisons between them easier. First, the simulations were done using the same current 120 mA in each of the configurations. Since the peak current density, which is responsible for burns, can be different for different configurations and values of contact impedance, a maximum current density was chosen (nearly 61.12 Am^{-2}) and simulations performed using the required current for some of the cases.

Table 1: Depths at which activation function is calculated

2.95 mm (s) ^a	32.47 mm
5.90 mm (f)	35.43 mm
8.86 mm (f) ^b	38.38 mm
11.81 mm (f)	41.33 mm
14.76 mm	44.28 mm
17.71 mm	47.24 mm
20.67 mm	50.19 mm
23.62 mm	53.14 mm
26.57 mm	56.10 mm
29.52 mm	59.05 mm

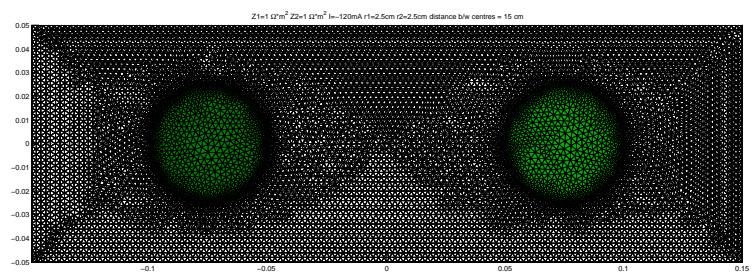
^as=skin, f=fat and rest are in muscle

^bthis depth is not available in Sec. 1.6 and 2.4

1 Simulations with current 120 mA

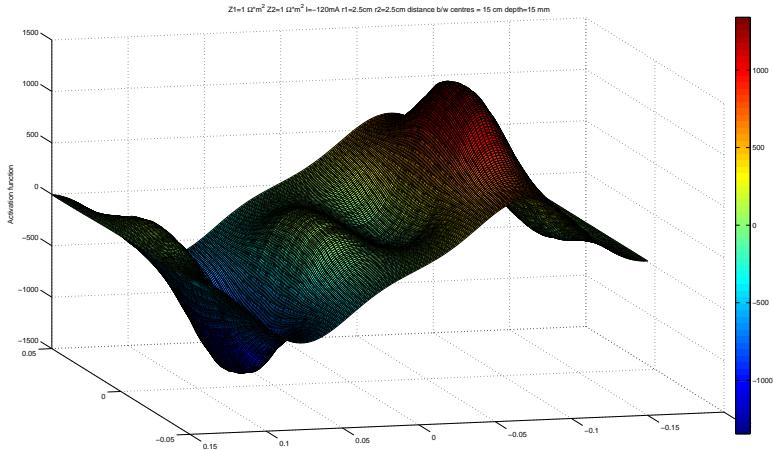
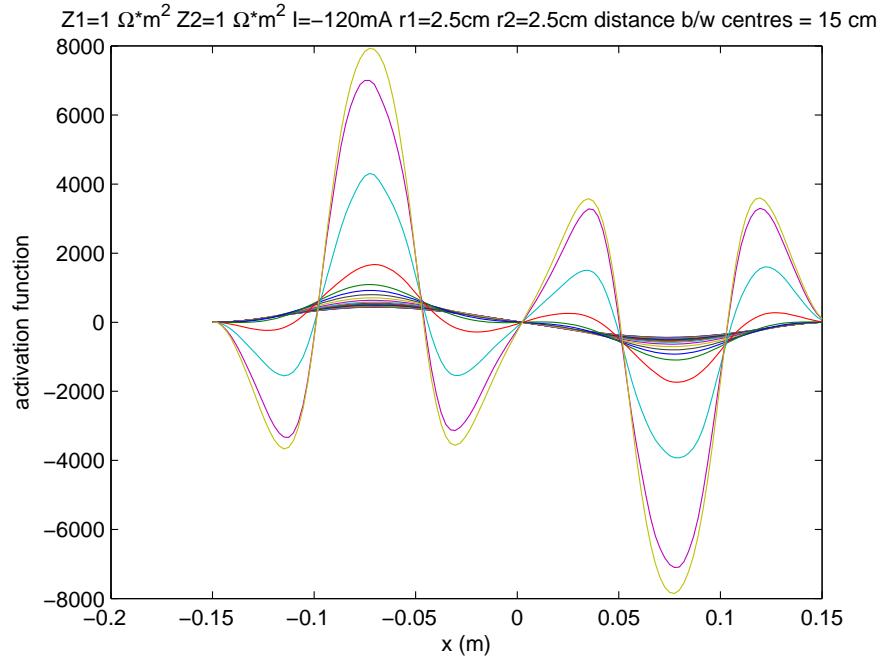
1.1

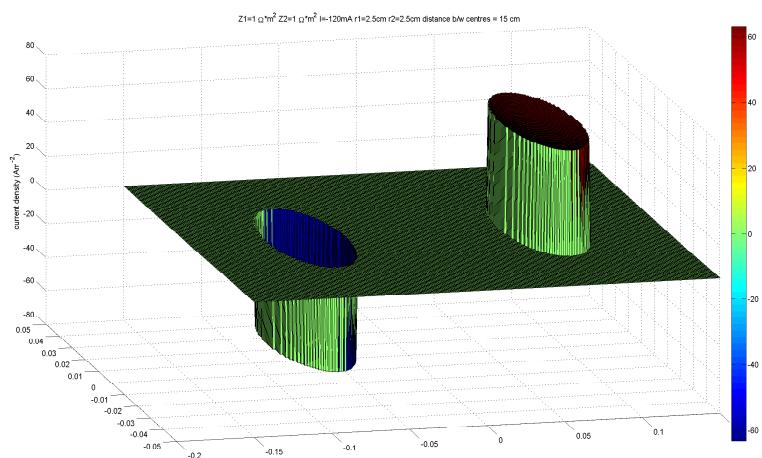
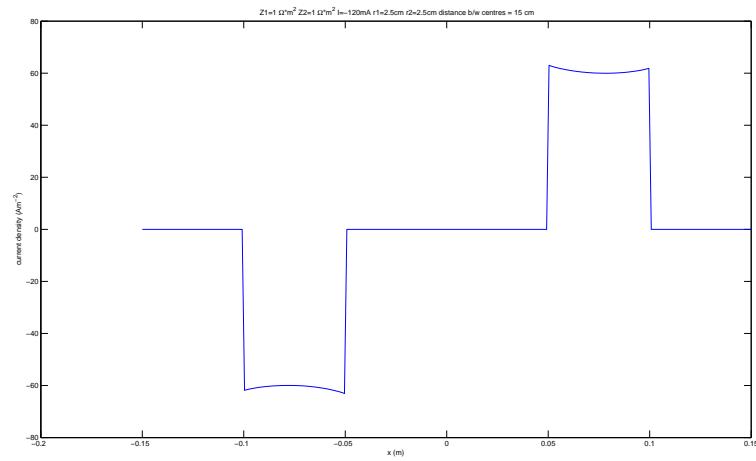
Side by side disk electrodes with radii 2.5 cm each and distance between centres 15 cm -

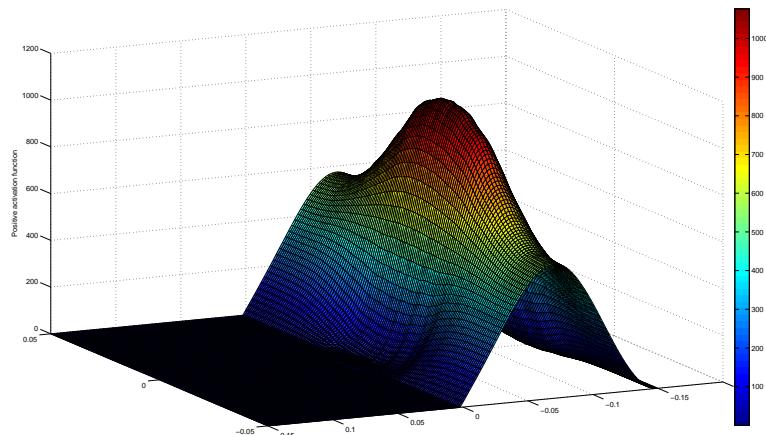
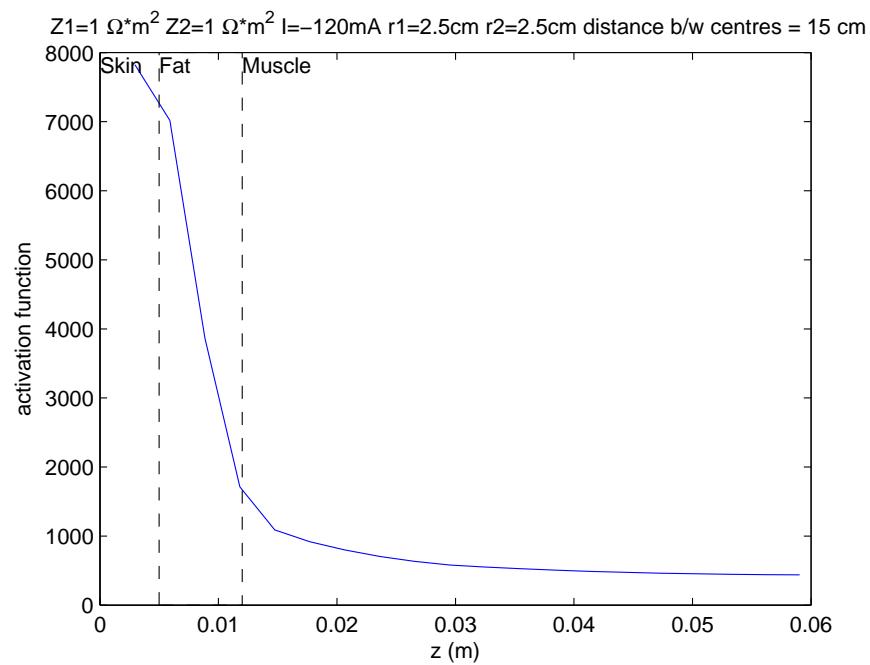


Parameters - $r_1=r_2=2.5$ cm, distance b/w centres=15 cm, $I=120$ mA, area= 19.635 cm^2

1.1.1 $Z_1=Z_2=1 \Omega m^2$

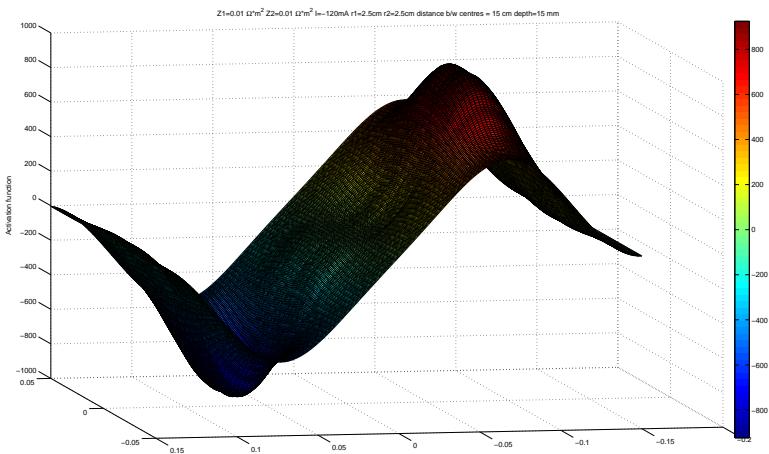
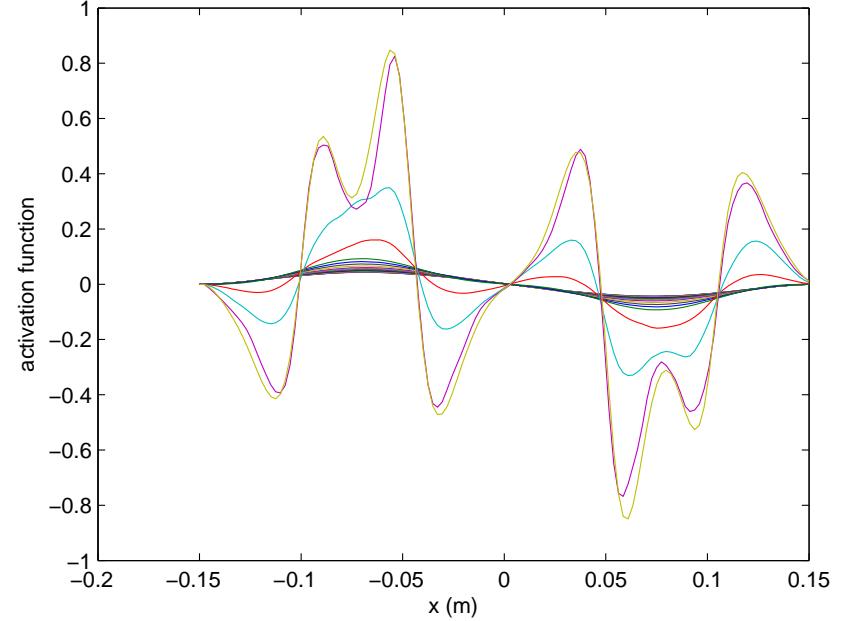




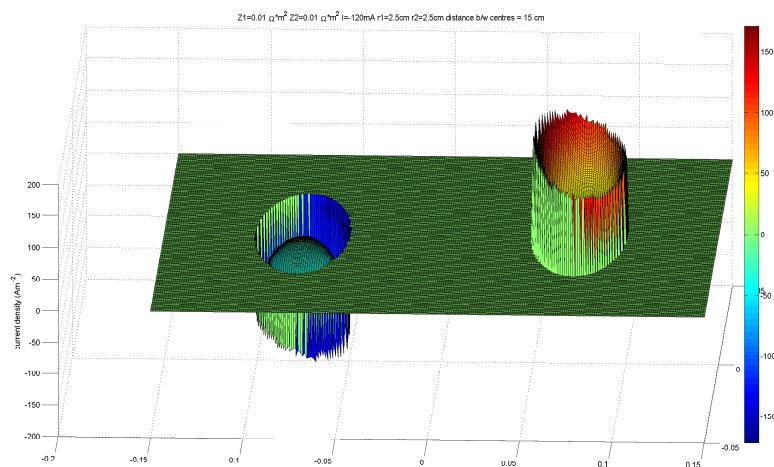
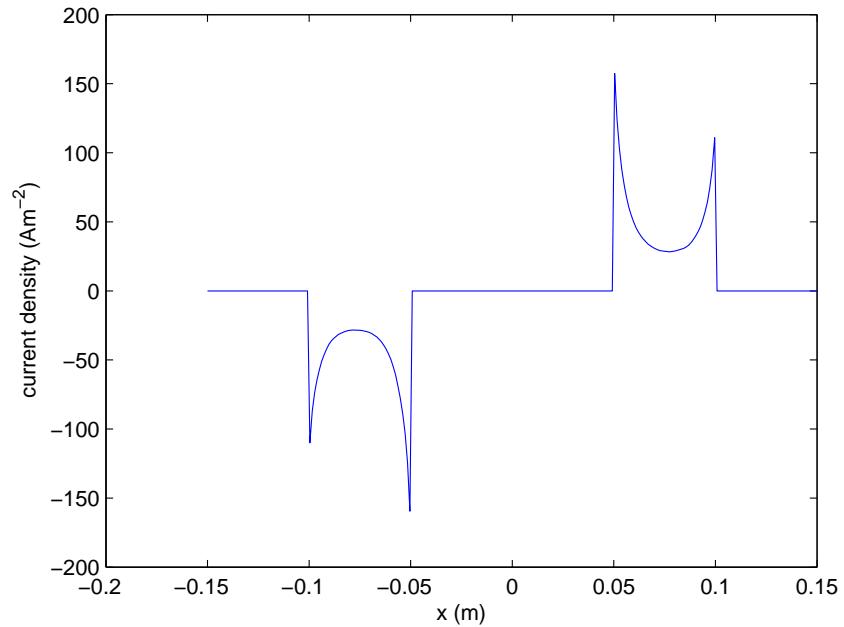


1.1.2 $Z_1=Z_2=0.01 \Omega m^2$

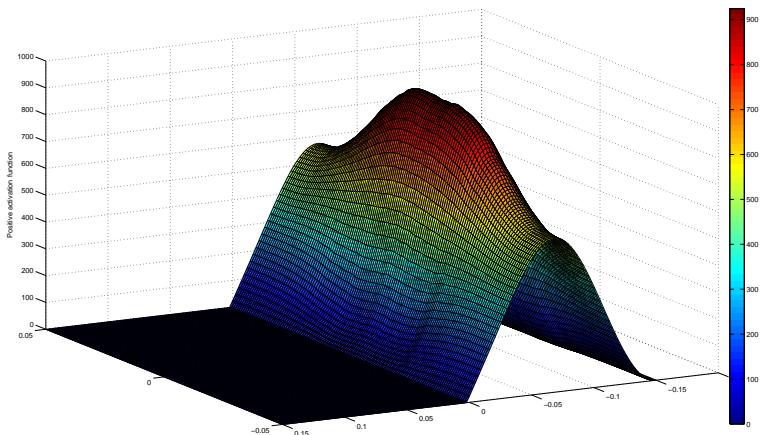
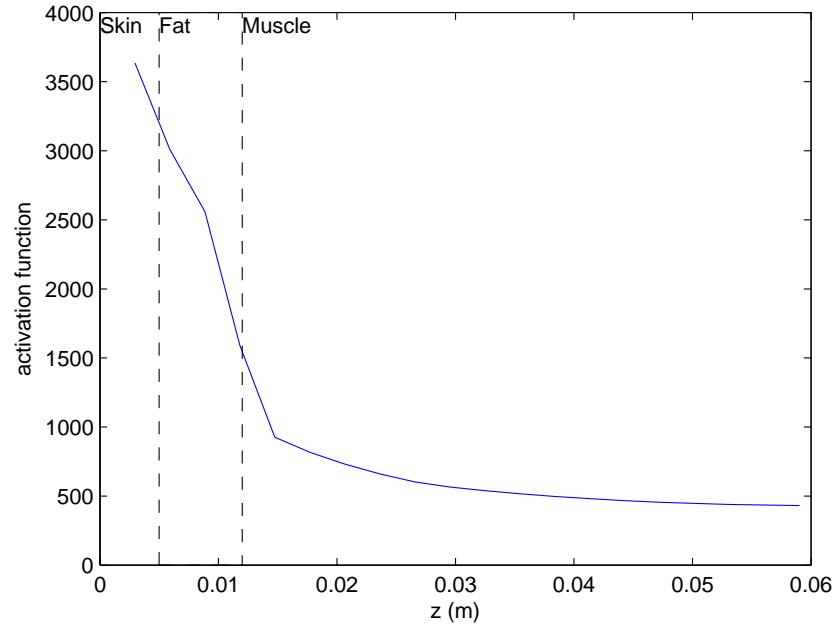
$Z1=0.01 \Omega m^2 Z2=0.01 \Omega m^2 I=-120mA r1=2.5cm r2=2.5cm$ distance b/w centres = 15 cm



$Z_1=0.01 \Omega \cdot m^2$ $Z_2=0.01 \Omega \cdot m^2$ $I=-120mA$ $r_1=2.5cm$ $r_2=2.5cm$ distance b/w centres = 15 cm

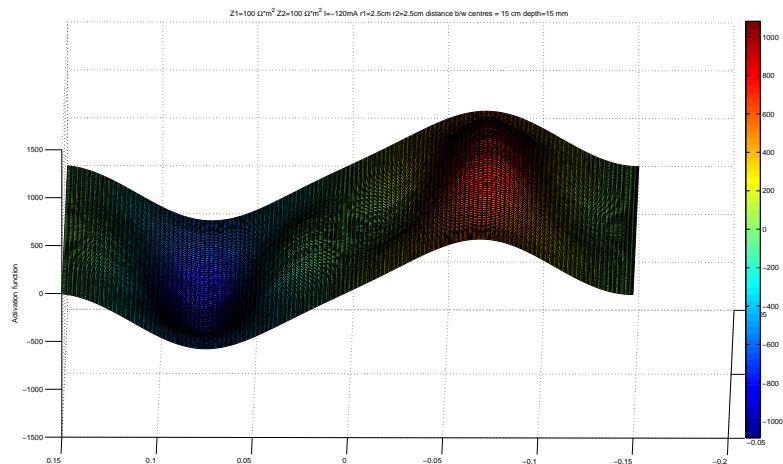
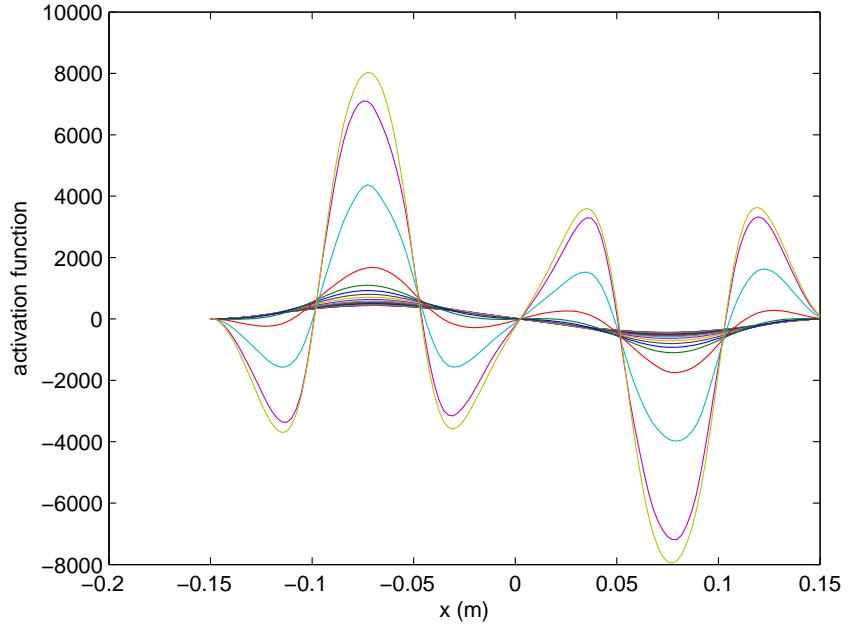


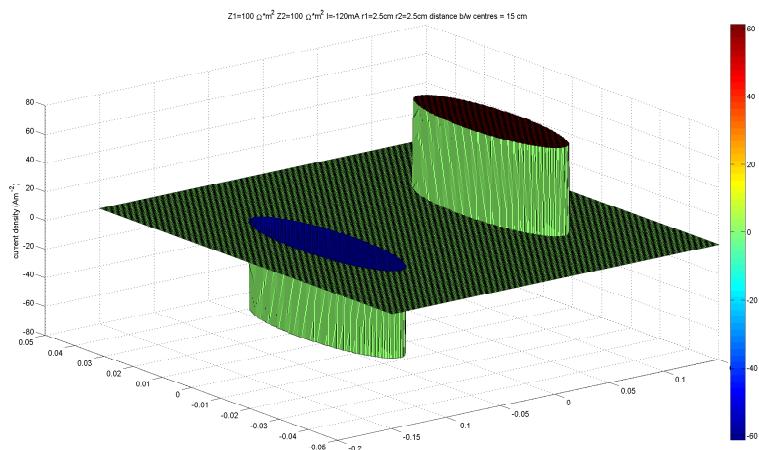
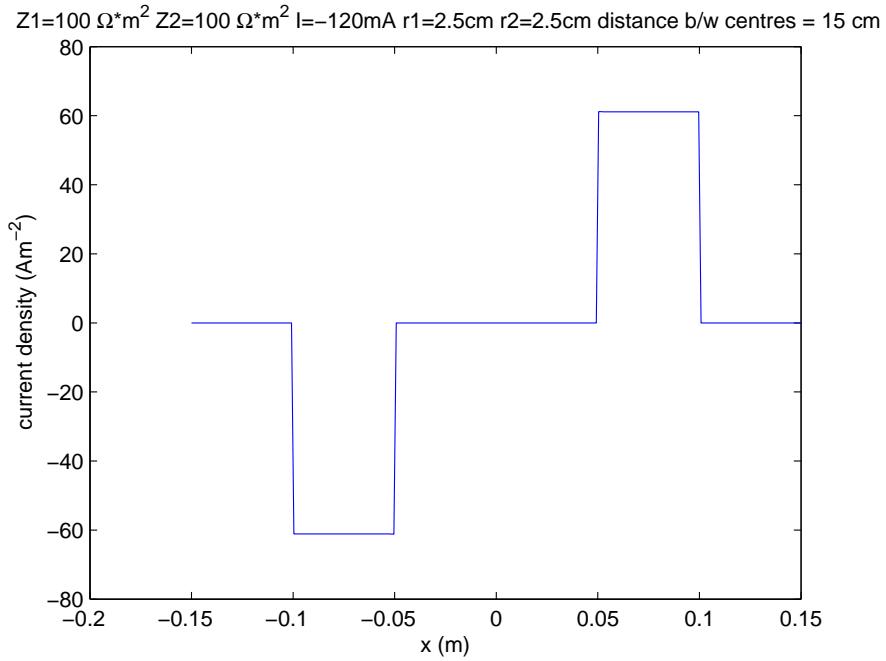
$Z_1=0.01 \Omega \cdot m^2$ $Z_2=0.01 \Omega \cdot m^2$ $I=-120mA$ $r_1=2.5cm$ $r_2=2.5cm$ distance b/w centres = 15 cm

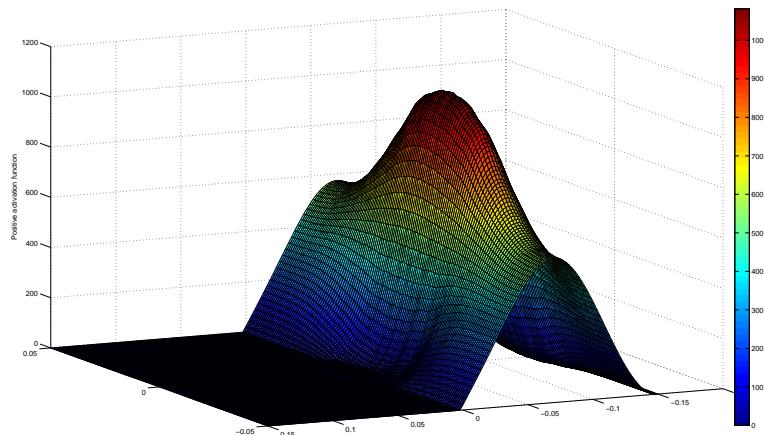
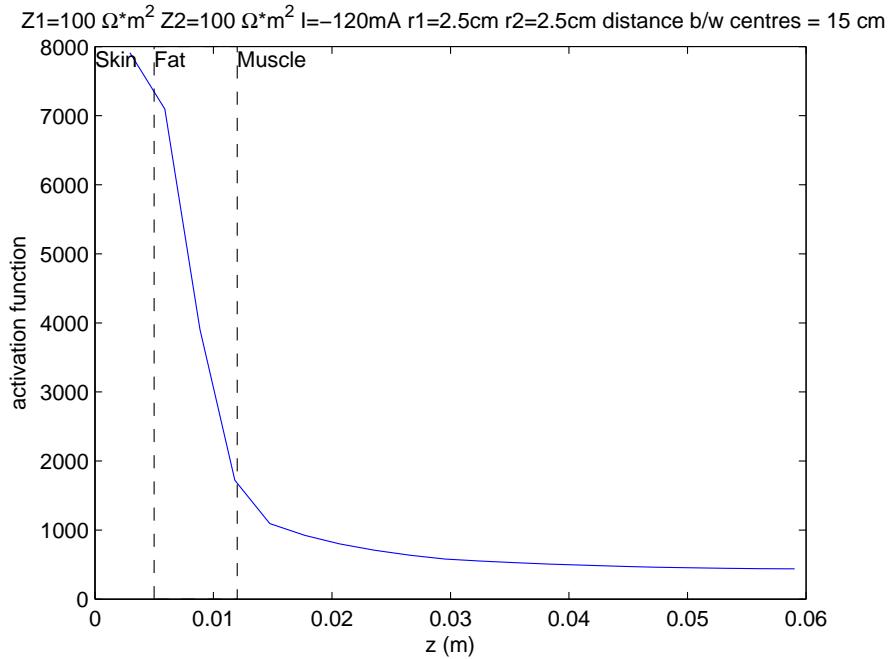


1.1.3 $Z_1=Z_2=100 \Omega\text{m}^2$

$Z1=100 \Omega\text{m}^2 Z2=100 \Omega\text{m}^2 I=-120\text{mA} r1=2.5\text{cm} r2=2.5\text{cm}$ distance b/w centres = 15 cm

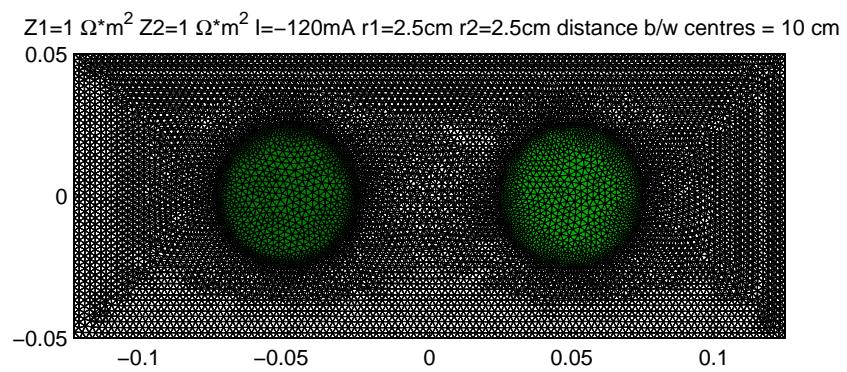






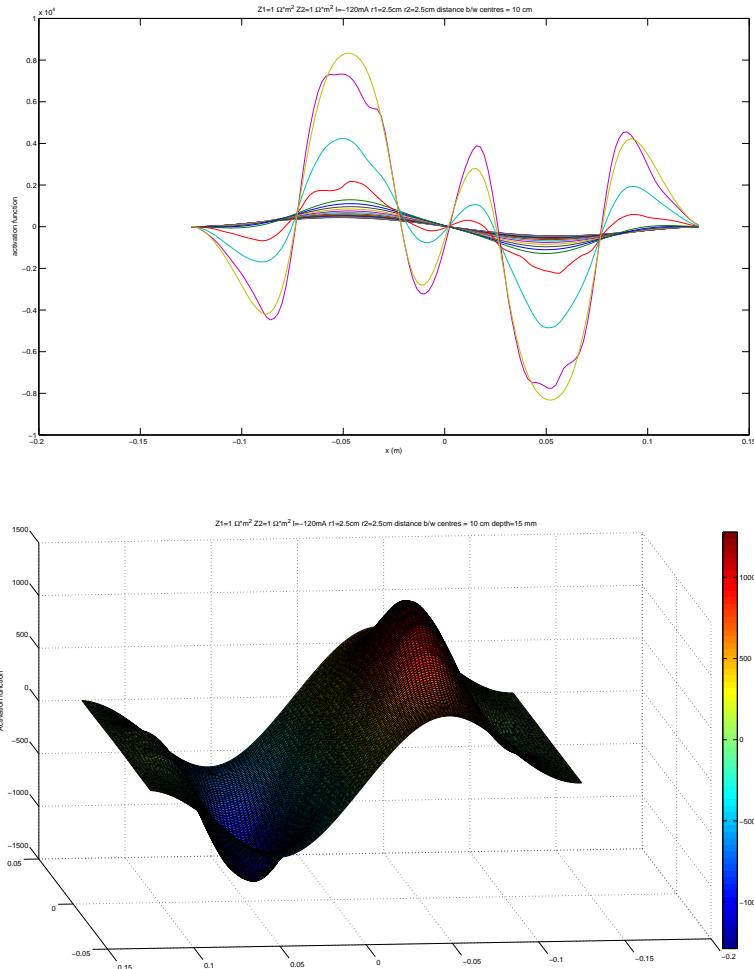
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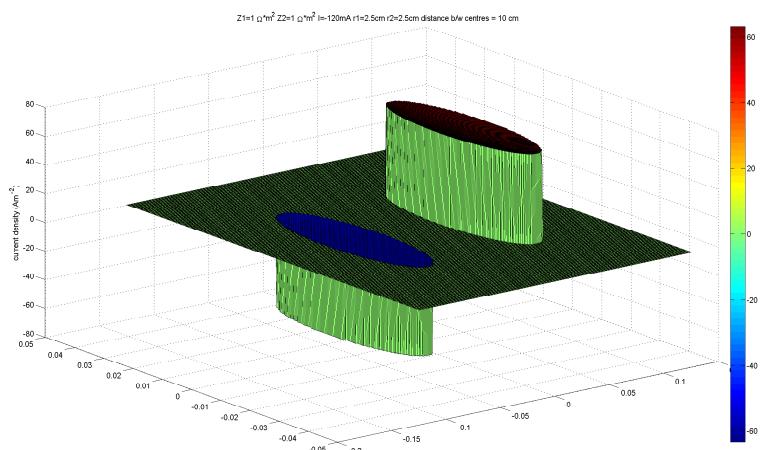
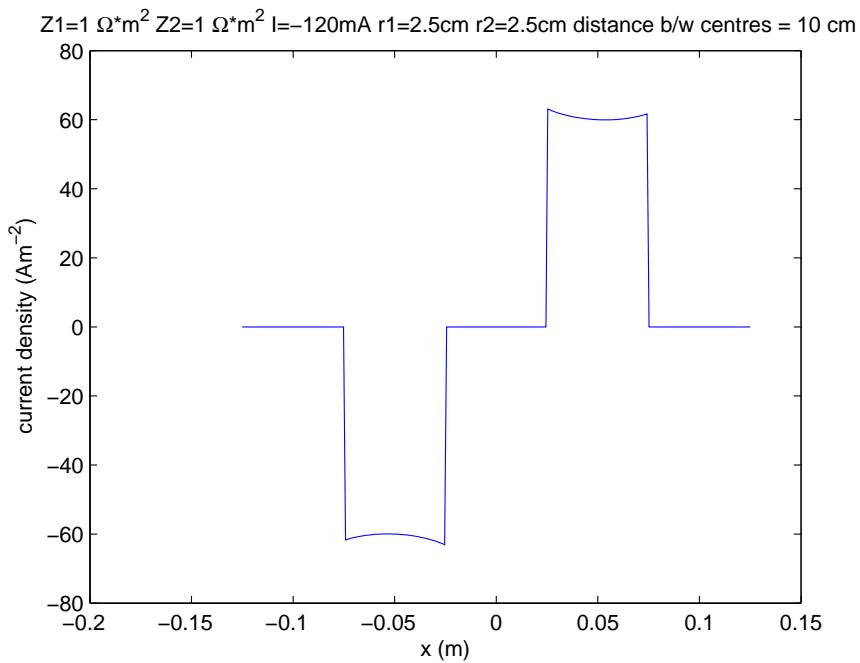
Side by side disk electrodes with radii 2.5 cm each and distance between centres 10 cm -

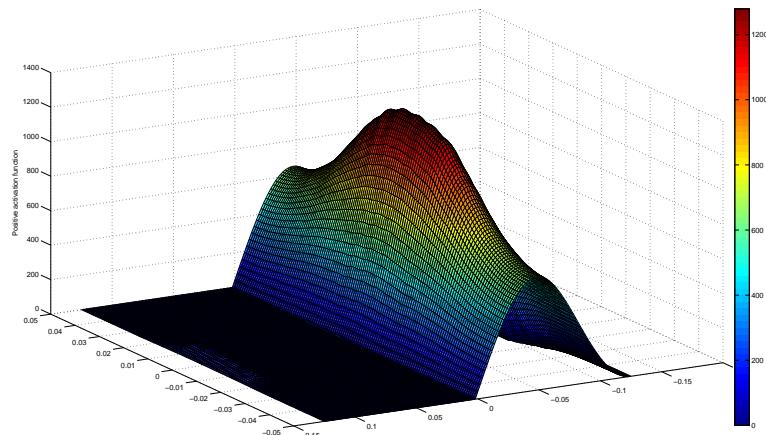
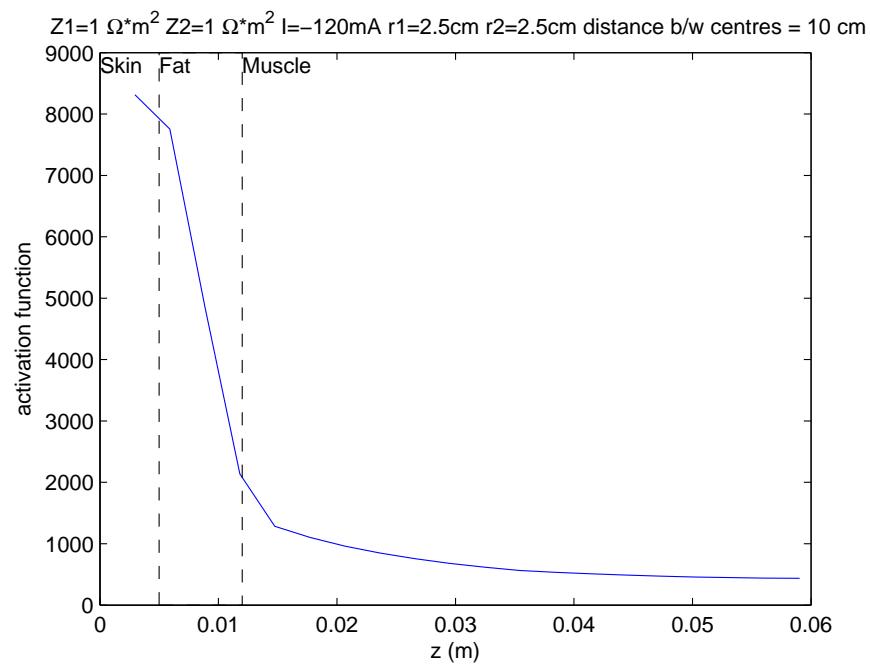


Parameters - $r_1=r_2=2.5$ cm, distance b/w centres=10 cm, $I=120$ mA, area=19.635 cm^2

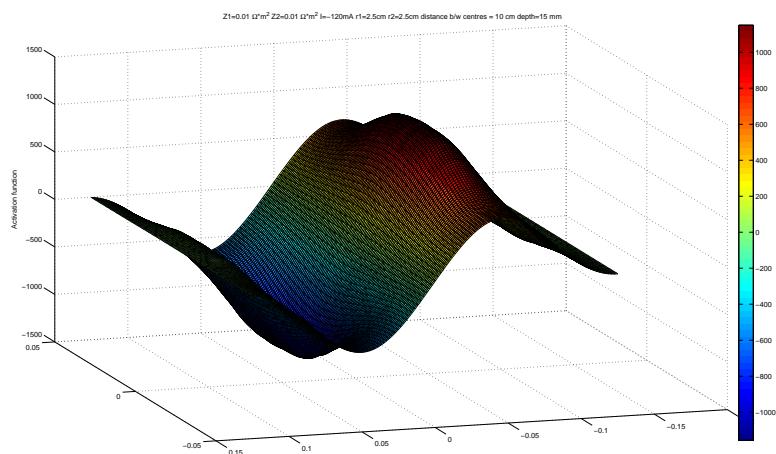
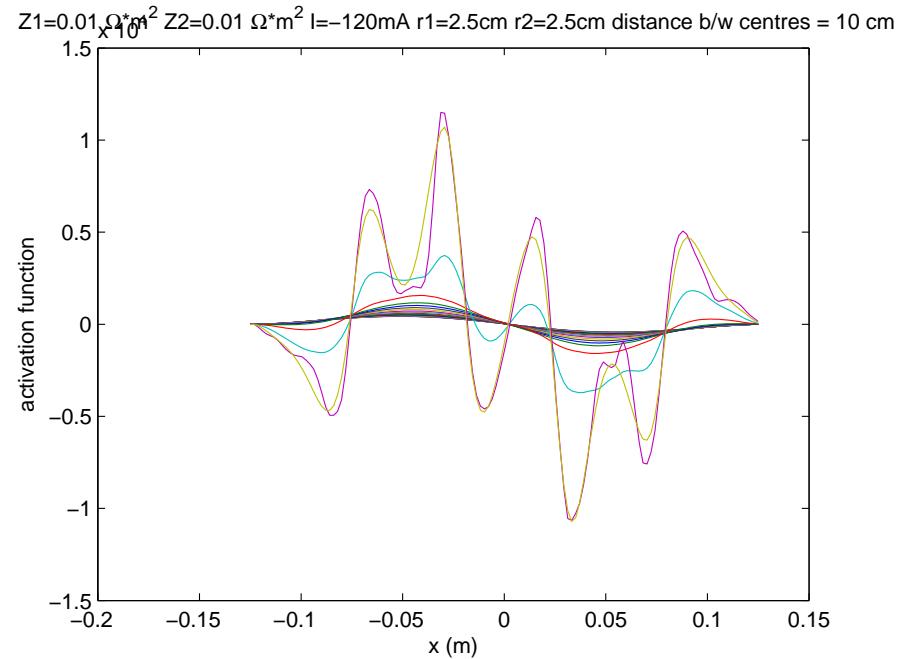
1.2.1 $Z_1=Z_2=1 \Omega\text{m}^2$



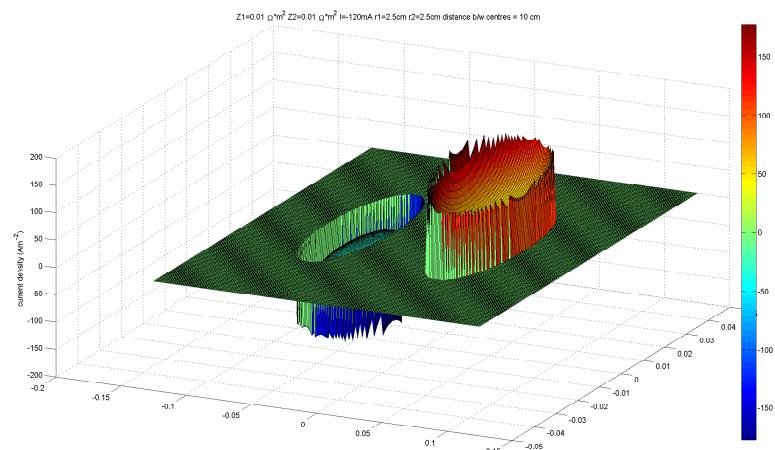
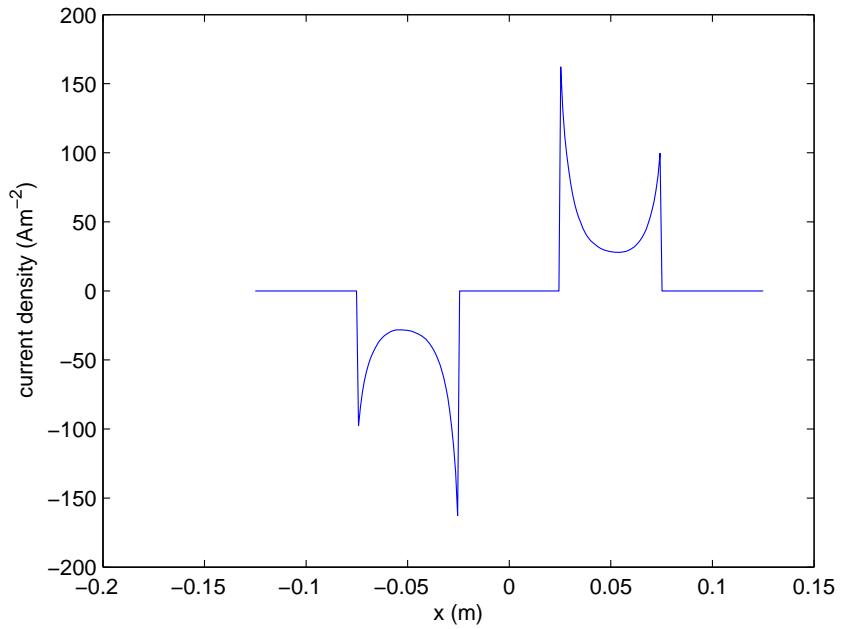




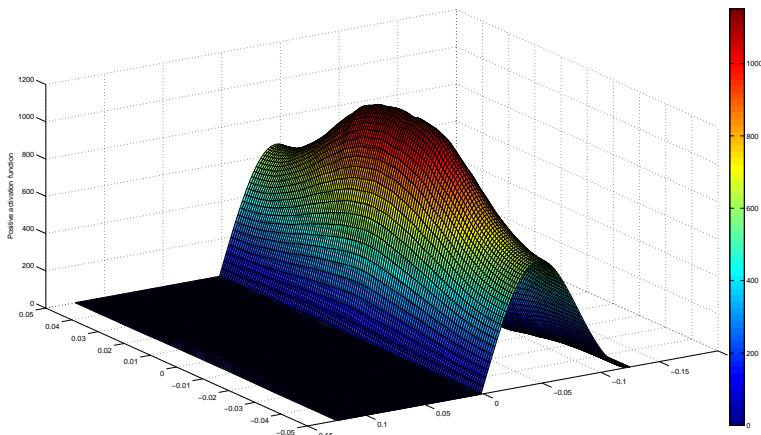
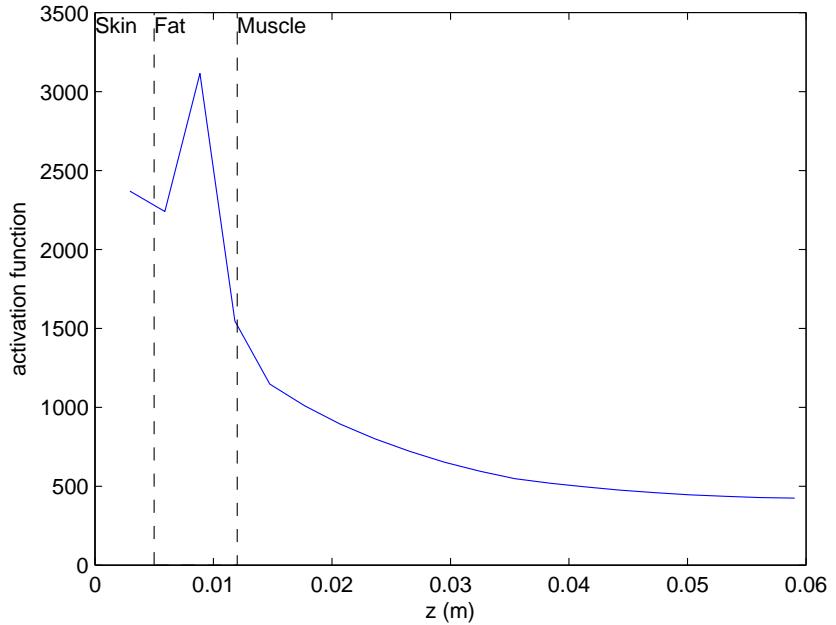
1.2.2 $Z_1=Z_2=0.01 \Omega m^2$



$$Z_1=0.01 \Omega \cdot m^2 \quad Z_2=0.01 \Omega \cdot m^2 \quad I=-120mA \quad r_1=2.5cm \quad r_2=2.5cm \quad \text{distance b/w centres} = 10 cm$$

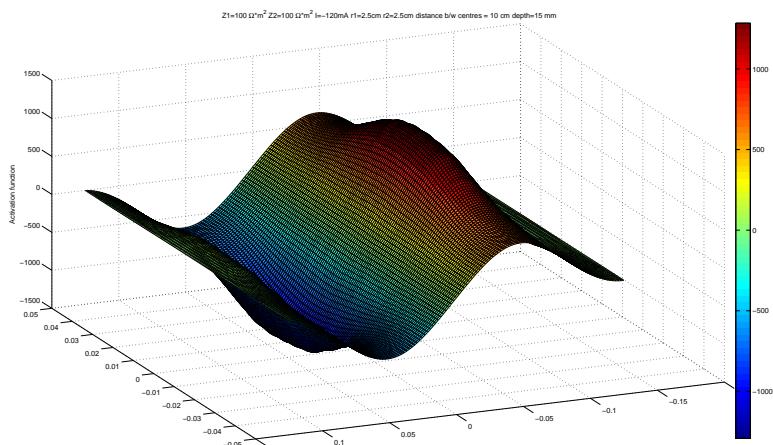
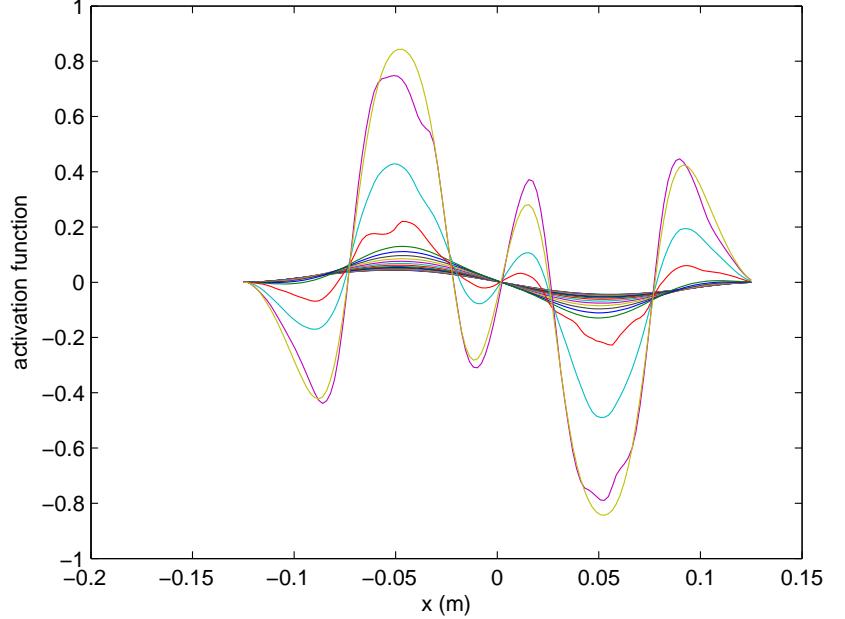


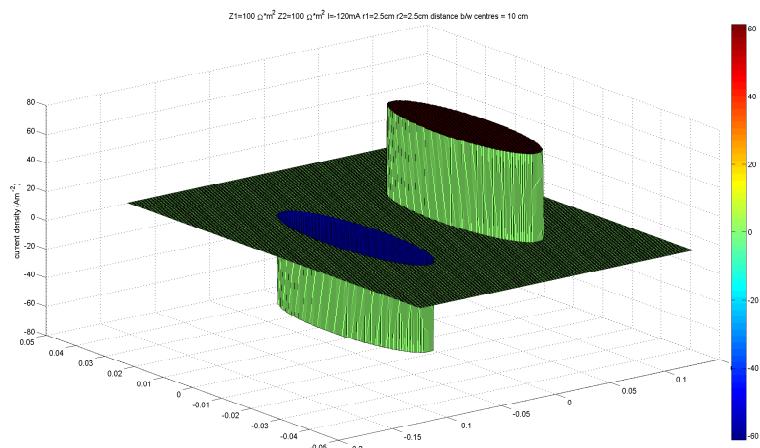
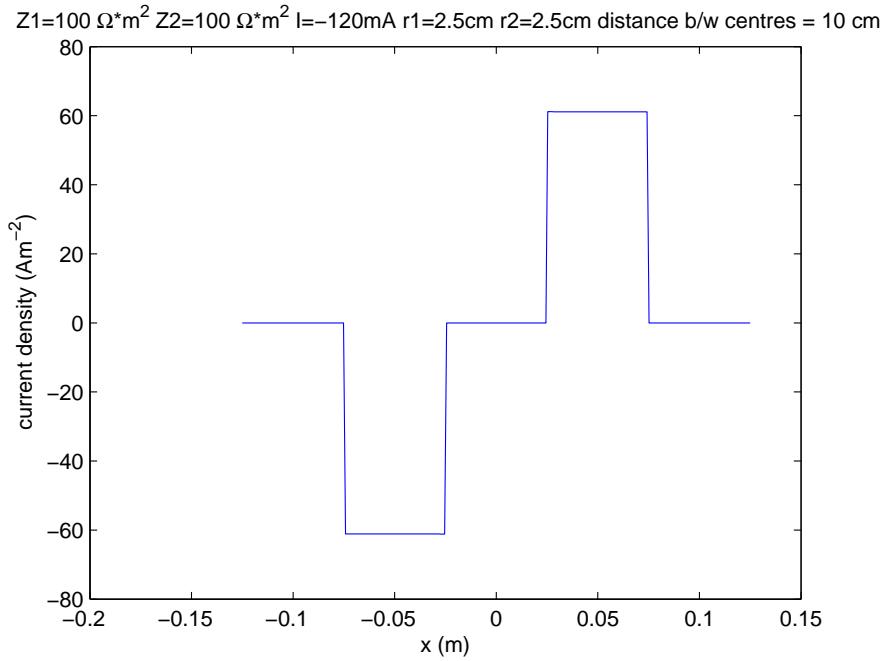
$$Z_1=0.01 \Omega \cdot m^2 \quad Z_2=0.01 \Omega \cdot m^2 \quad I=-120mA \quad r_1=2.5cm \quad r_2=2.5cm \quad \text{distance b/w centres} = 10 \text{ cm}$$

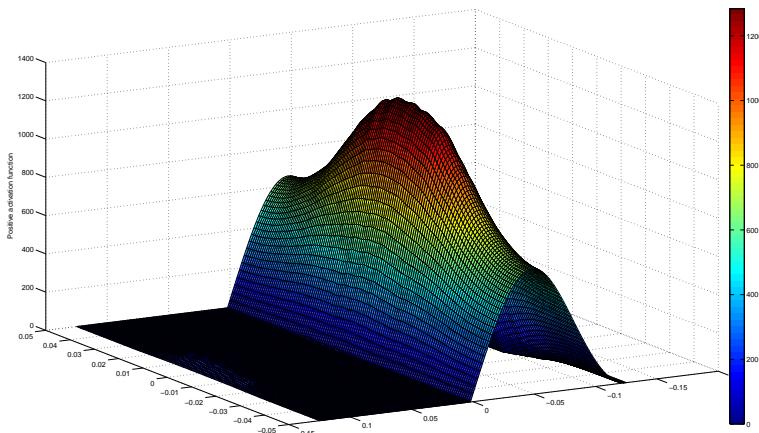
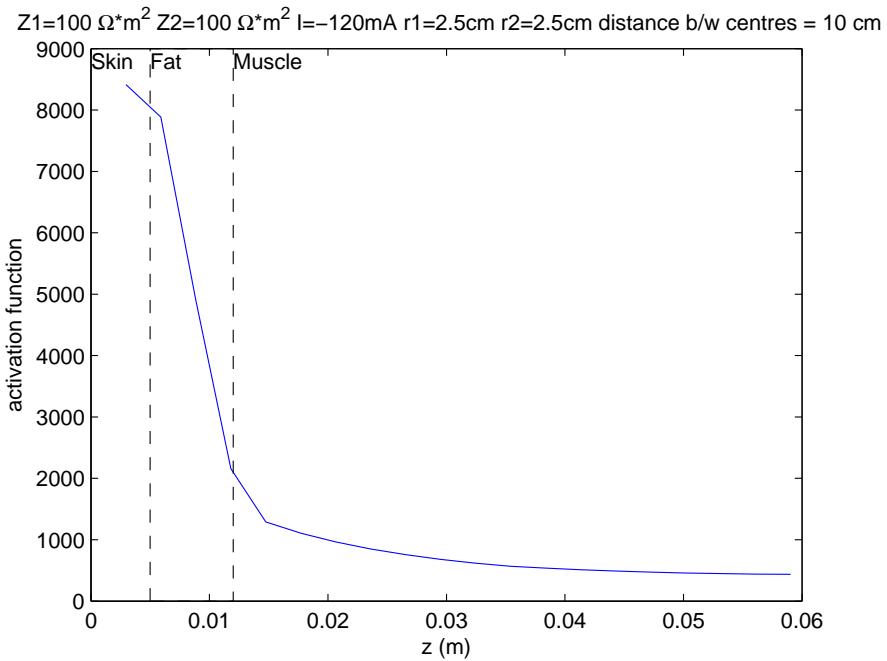


1.2.3 $Z_1=Z_2=100 \Omega\text{m}^2$

$Z1=100 \Omega\text{m}^2 Z2=100 \Omega\text{m}^2 I=-120\text{mA} r1=2.5\text{cm} r2=2.5\text{cm}$ distance b/w centres = 10 cm





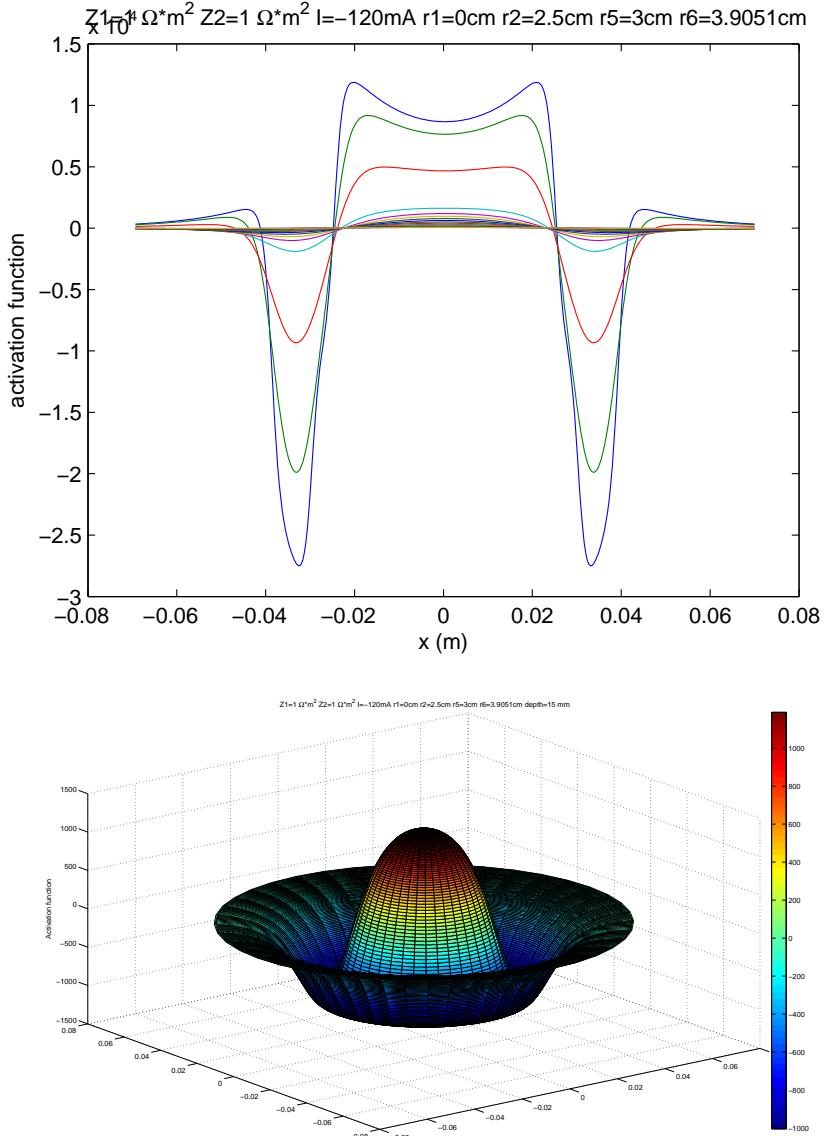


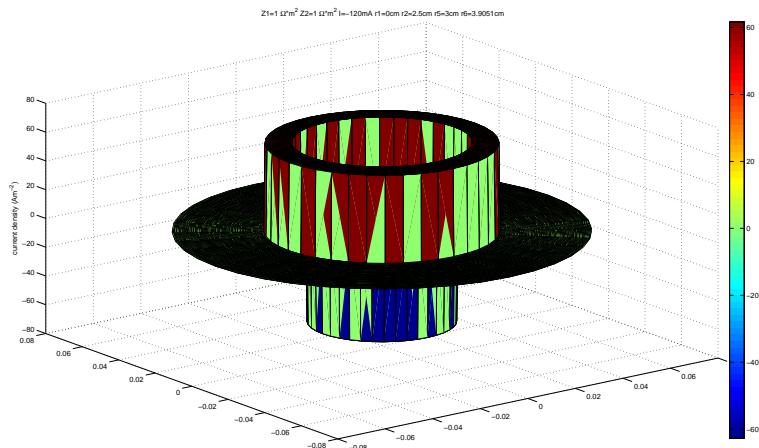
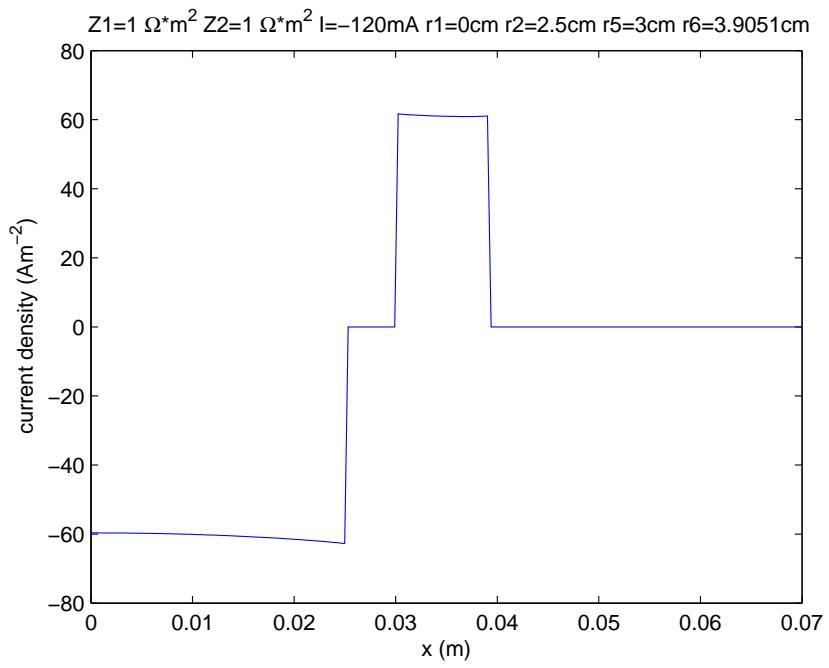
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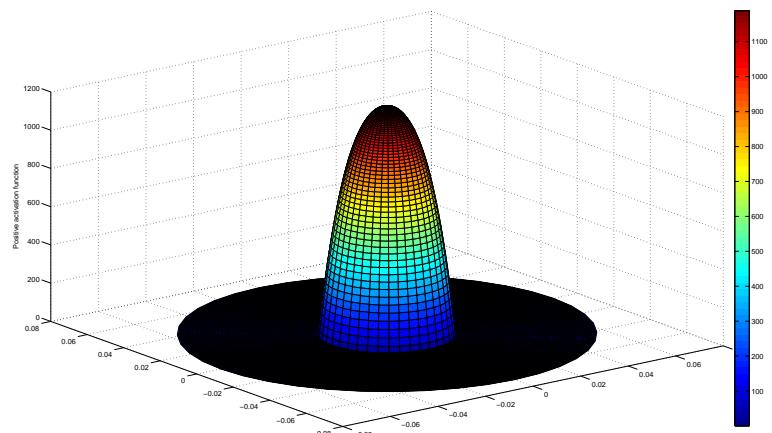
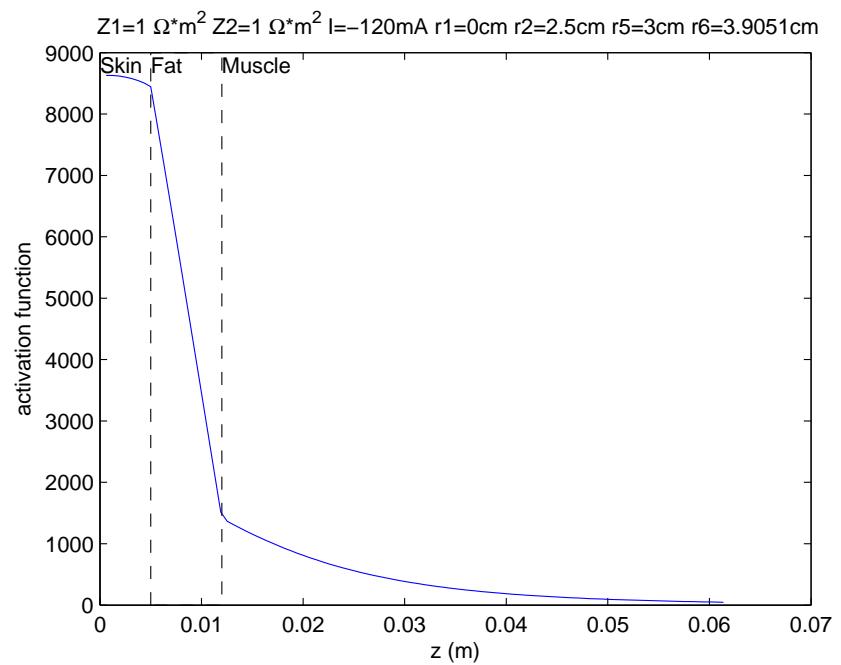
Concentric disk and ring electrodes. Parameters -

Inner electrode: $r_1=0$ cm, $r_2=2.5$ cm, area= 19.635 cm^2 , Outer electrode: $r_5=3.0$ cm, $r_6=3.9051$ cm, area= 19.635 cm^2 , $I=120$ mA

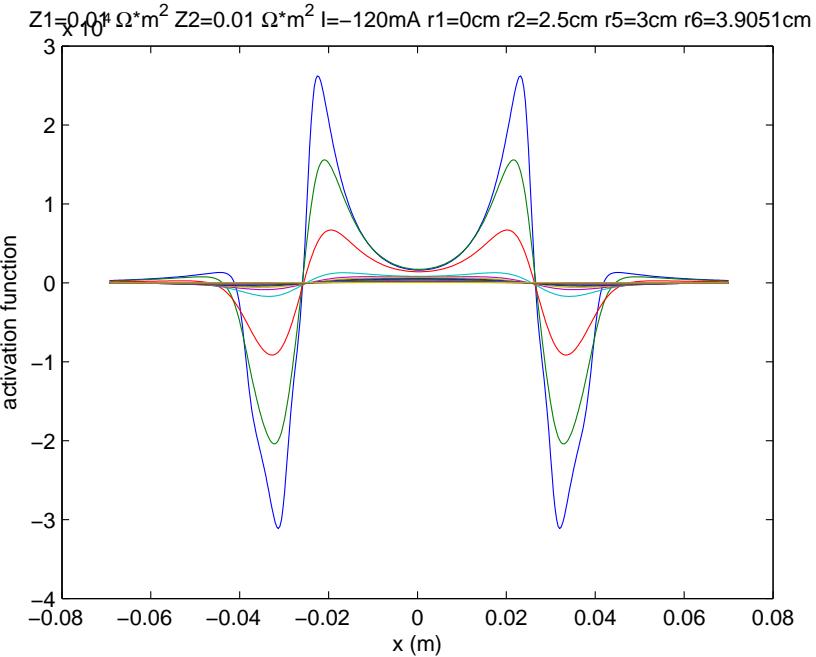
1.3.1 $Z_1=Z_2=1 \Omega\text{m}^2$



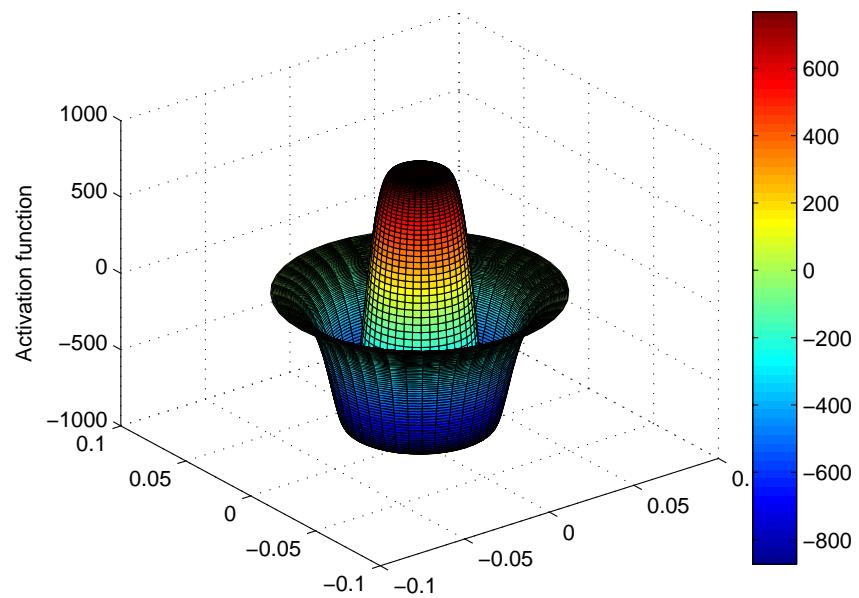


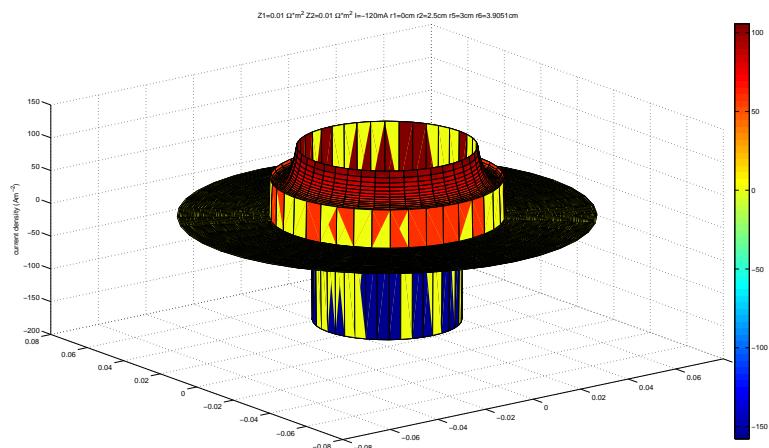
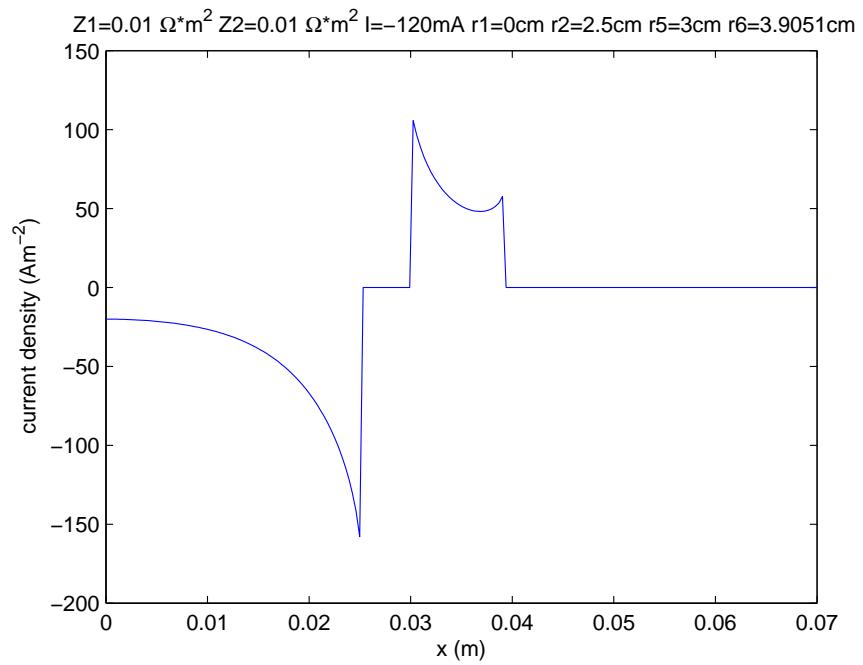


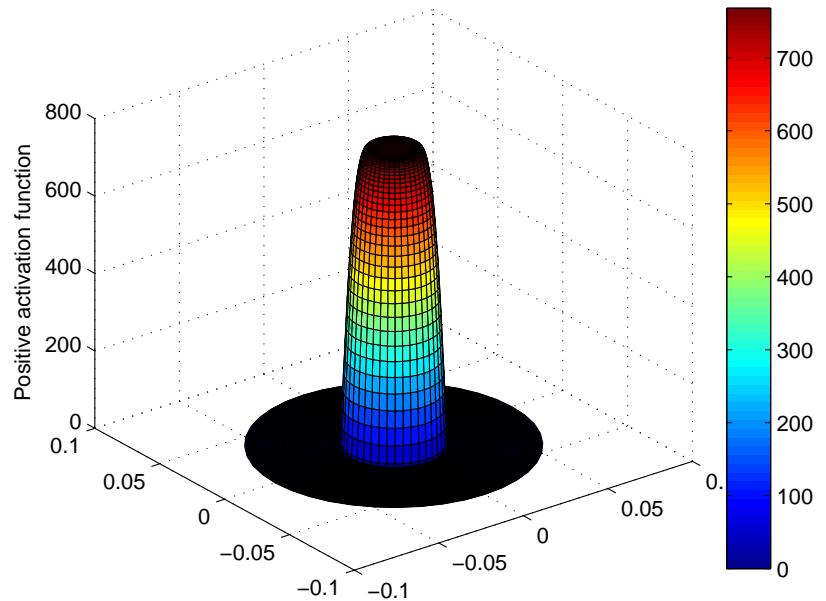
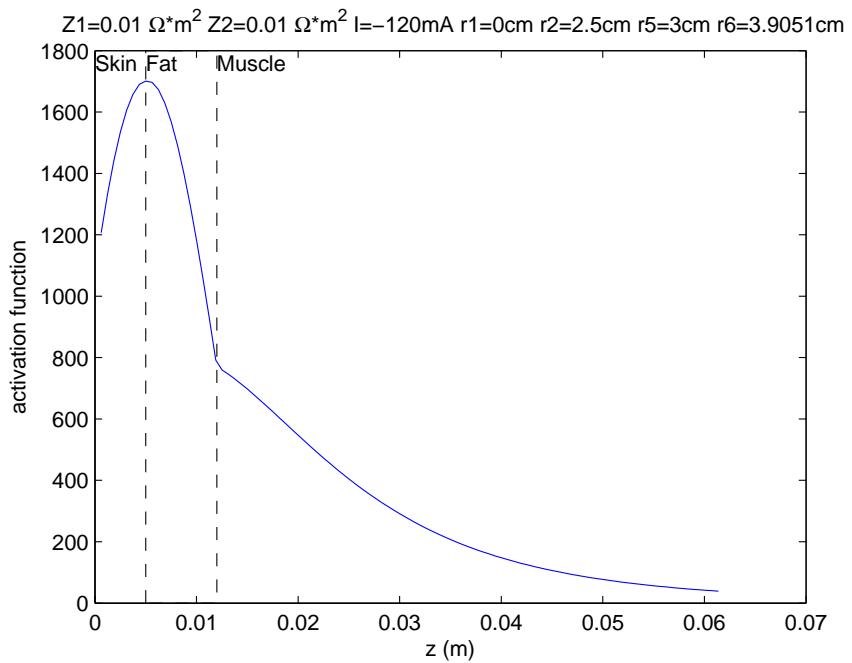
1.3.2 $Z_1=Z_2=0.01 \Omega \cdot m^2$



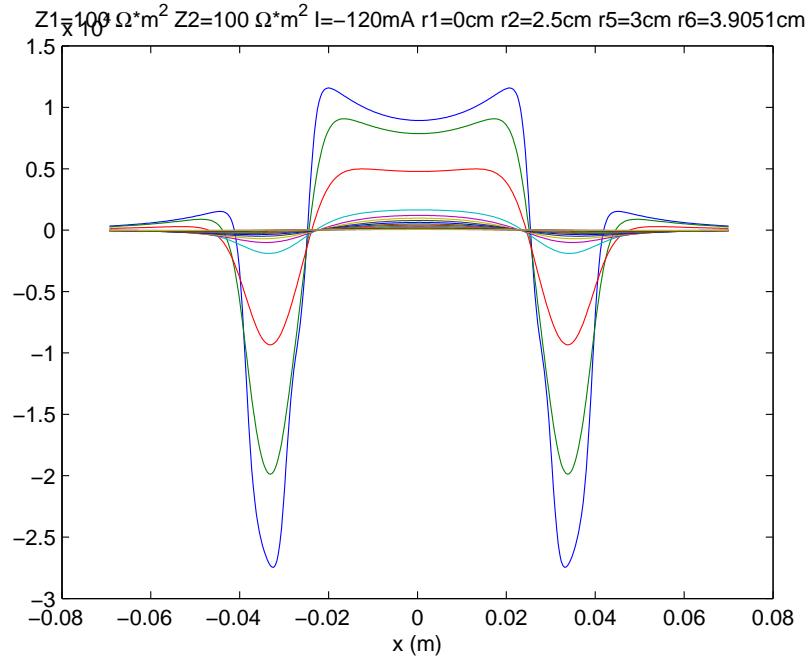
$0.01 \Omega \cdot m^2 Z2=0.01 \Omega \cdot m^2 I=-120mA r1=0cm r2=2.5cm r5=3cm r6=3.9051cm$ depth=15 mm



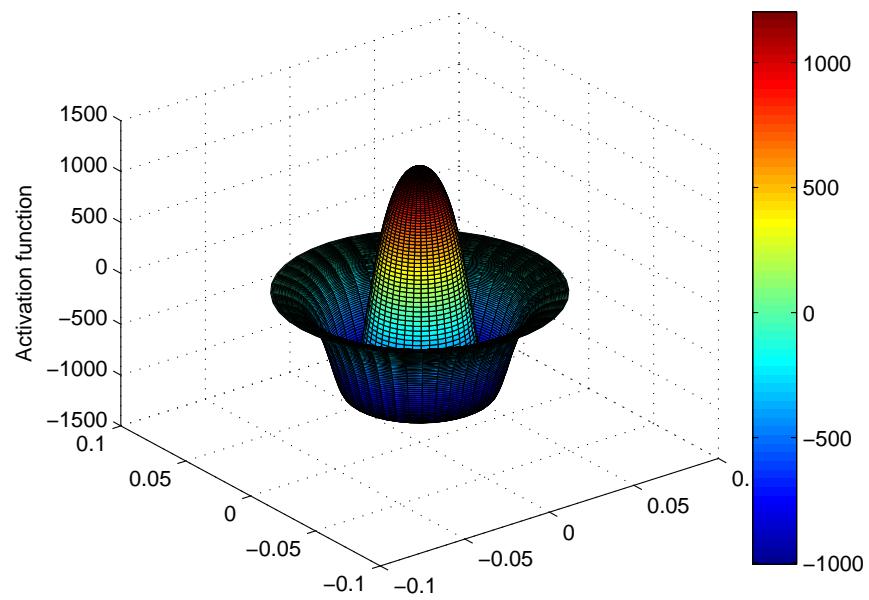


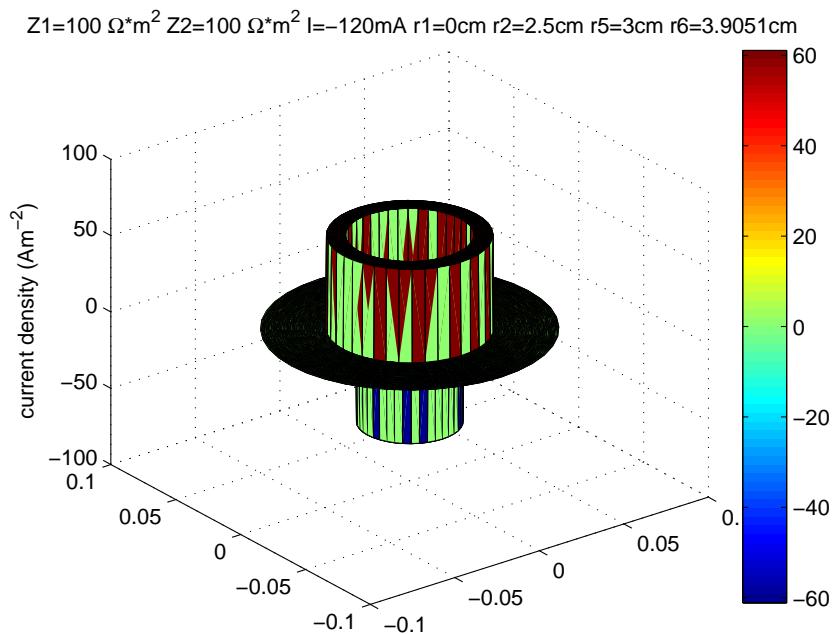
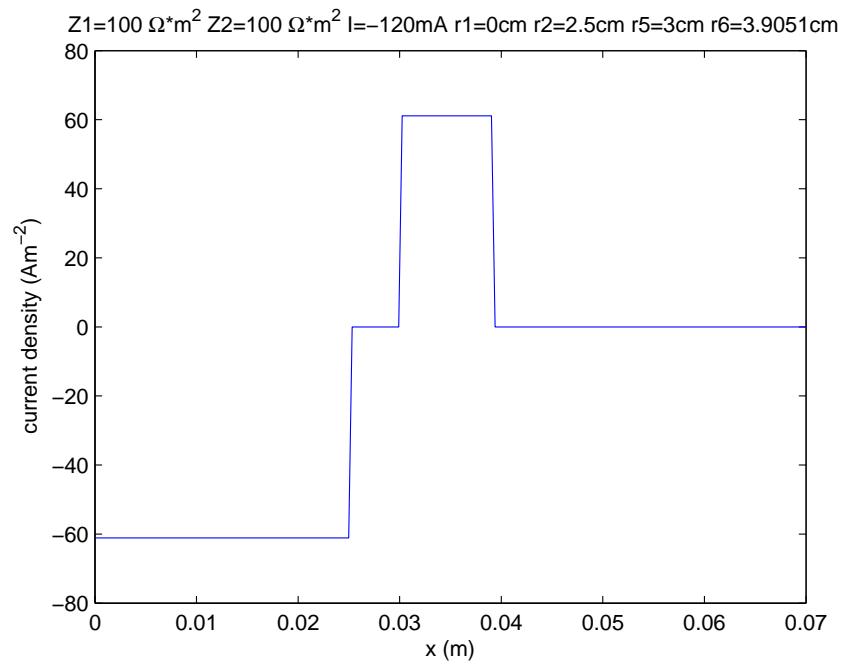


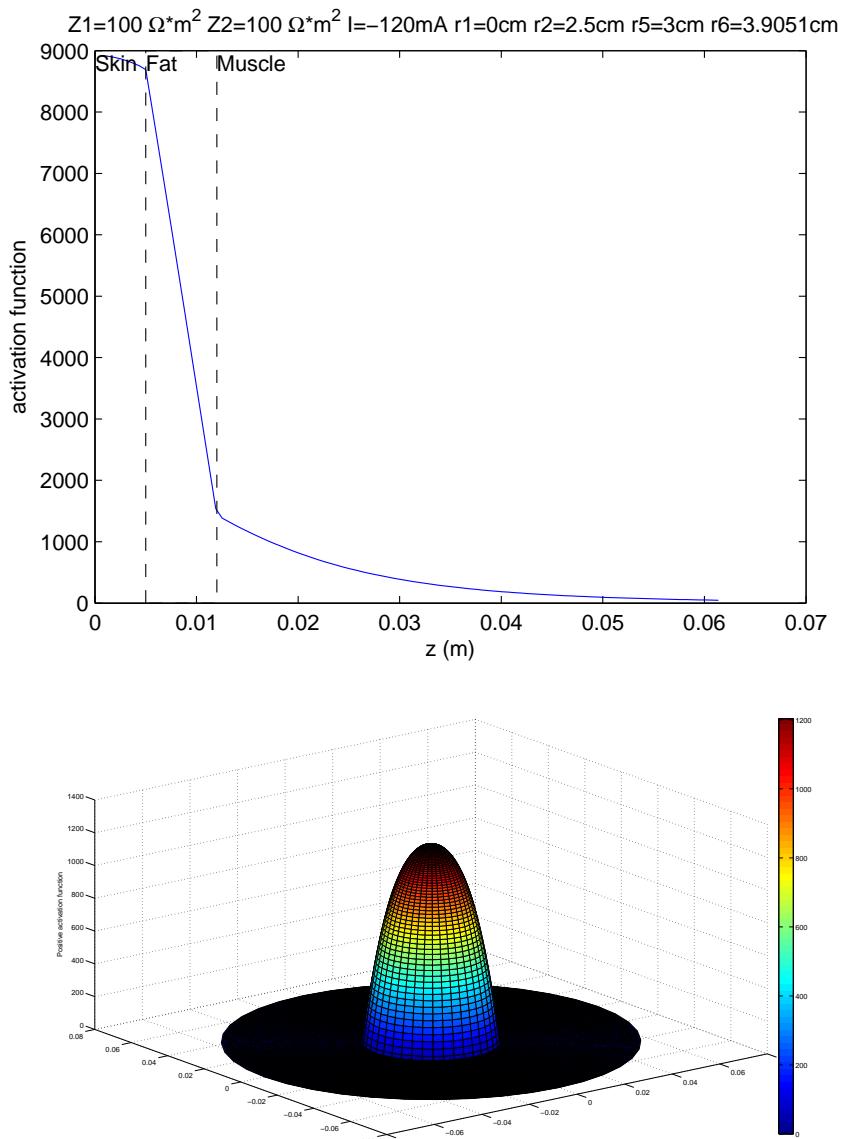
1.3.3 $Z_1=Z_2=100 \Omega\text{m}^2$



$\cdot 100 \Omega\text{m}^2 Z_2=100 \Omega\text{m}^2 l=-120\text{mA} r1=0\text{cm} r2=2.5\text{cm} r5=3\text{cm} r6=3.9051\text{cm depth}=15 \text{ mm}$





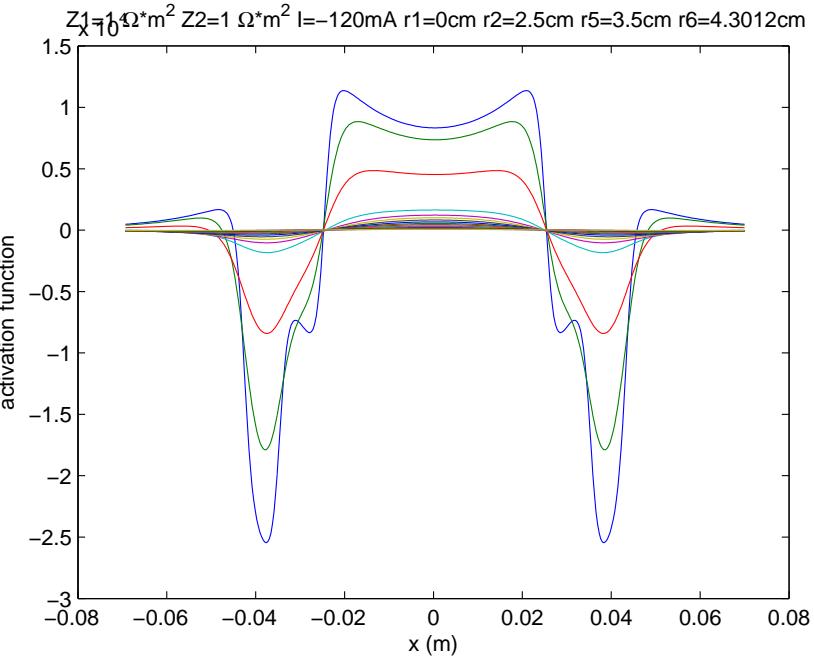


1.4

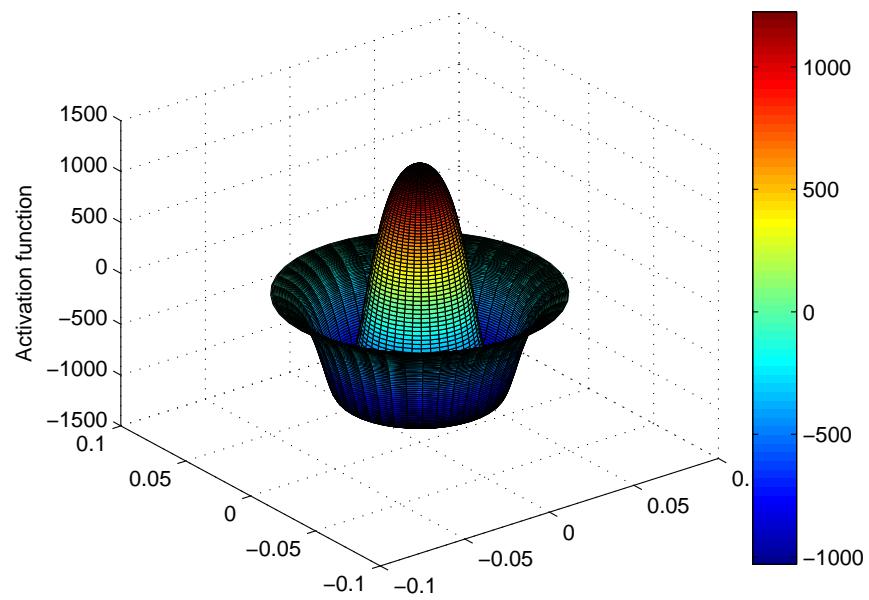
Concentric disk and ring electrodes. Parameters -

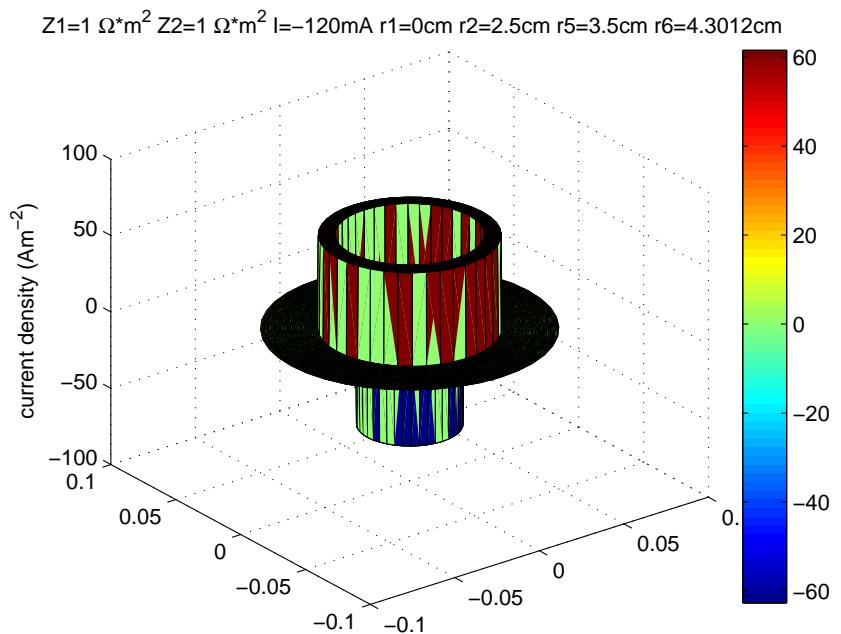
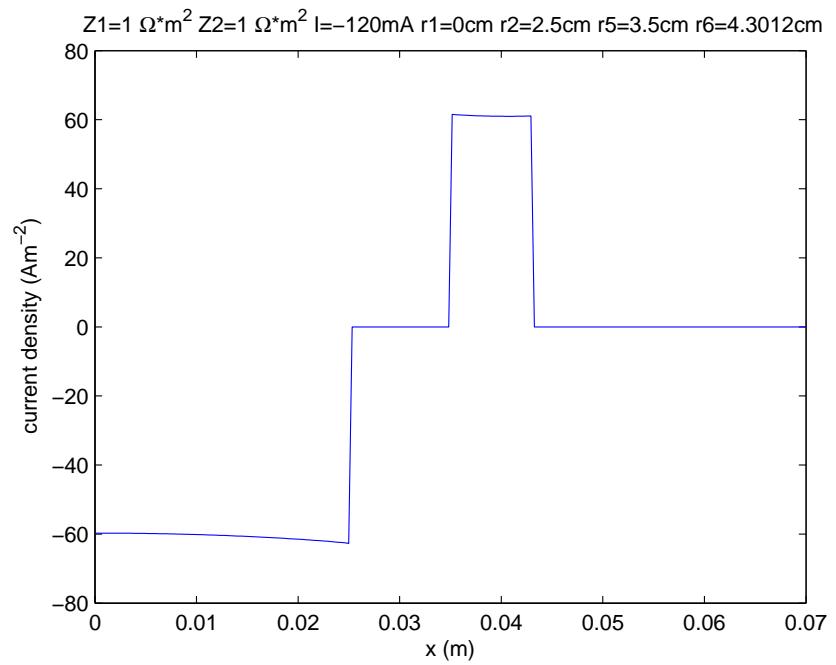
Inner electrode: $r_1=0 \text{ cm}$, $r_2=2.5 \text{ cm}$, area= 19.635 cm^2 , Outer electrode:
 $r_5=3.5 \text{ cm}$, $r_6=4.3012 \text{ cm}$, area= 19.635 cm^2 , $I=120 \text{ mA}$

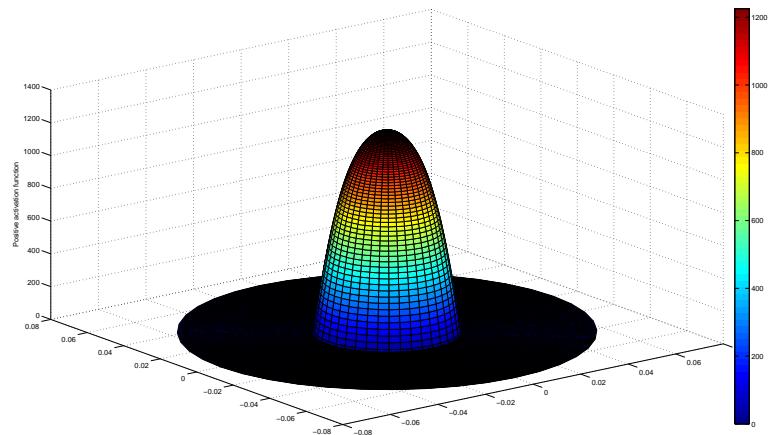
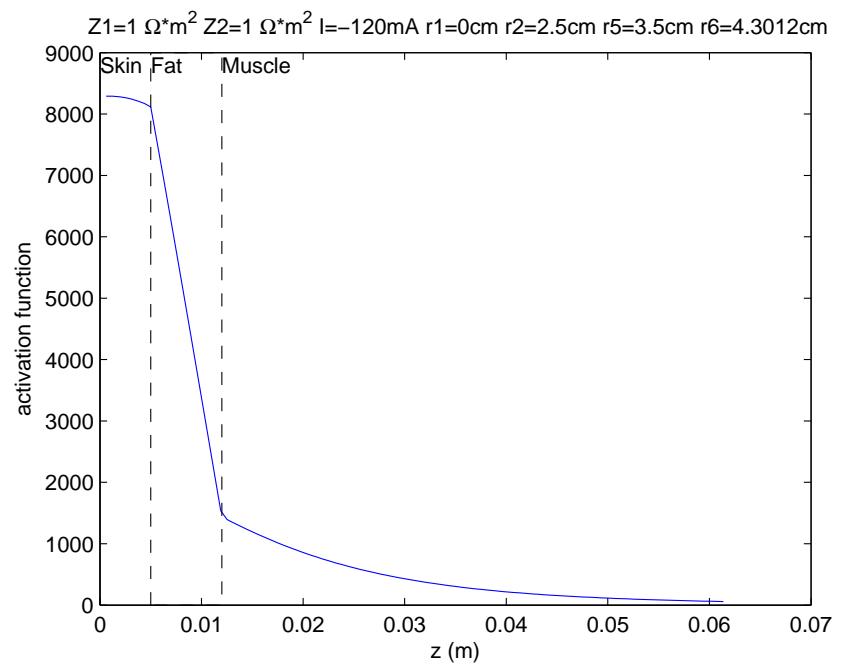
1.4.1 $Z_1=Z_2=1 \Omega\text{m}^2$



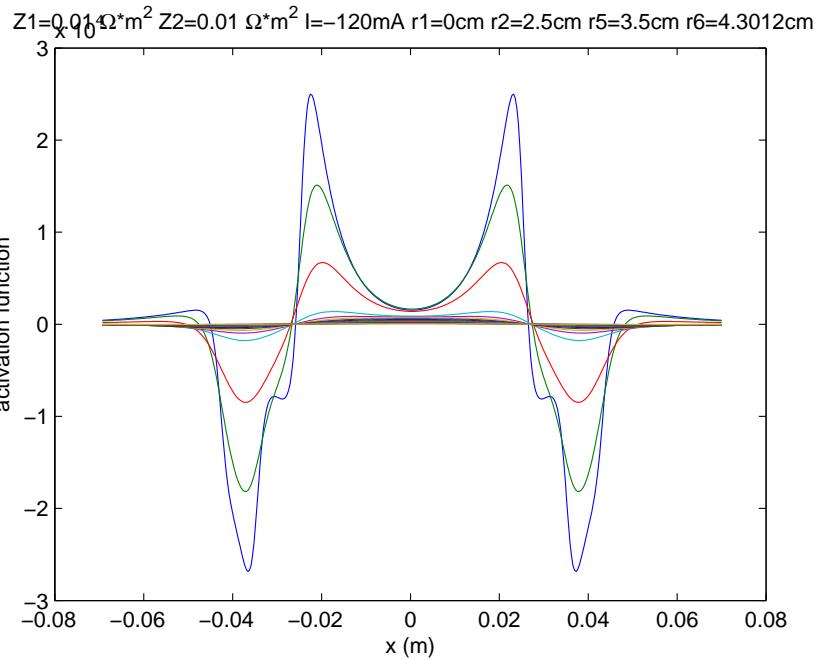
$I=1 \Omega\text{m}^2 Z_2=1 \Omega\text{m}^2 I=-120\text{mA} r1=0\text{cm} r2=2.5\text{cm} r5=3.5\text{cm} r6=4.3012\text{cm}$ depth=15 mm



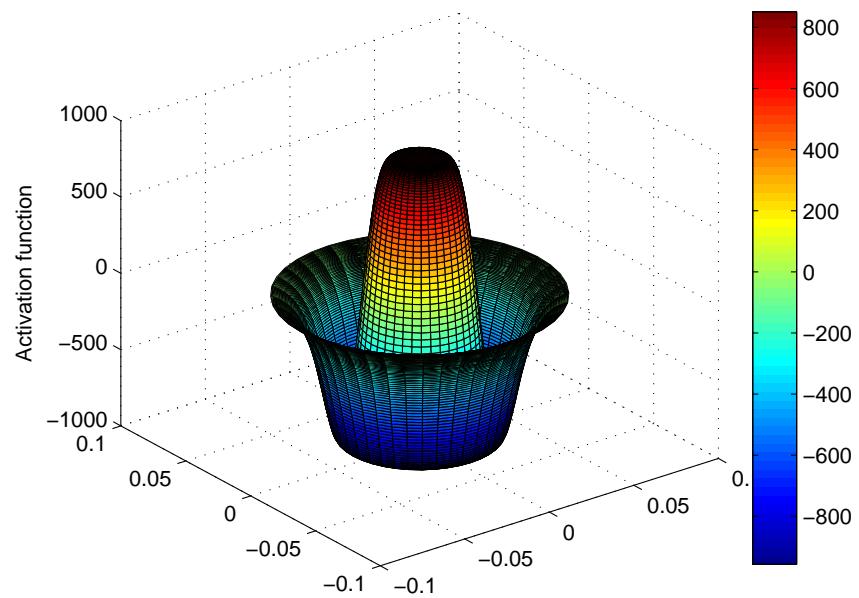


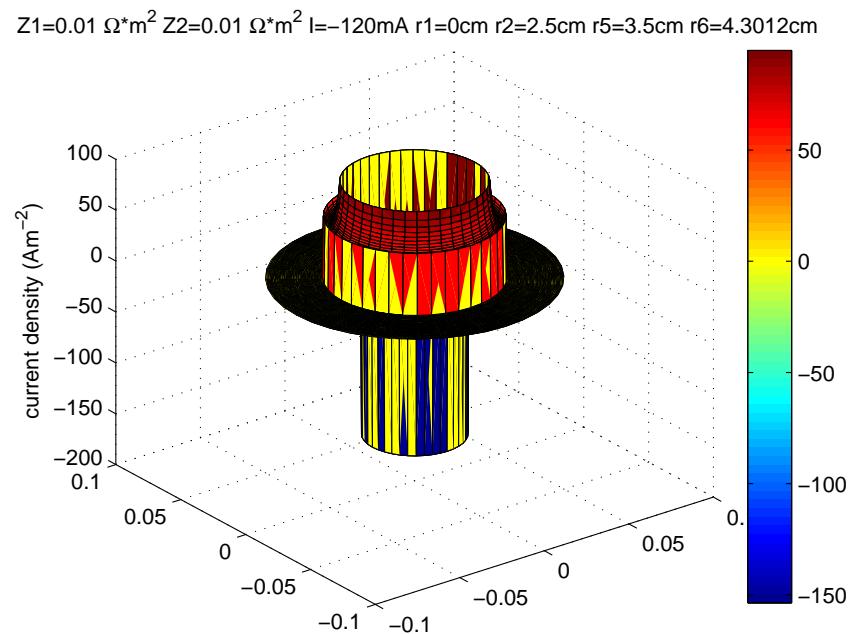
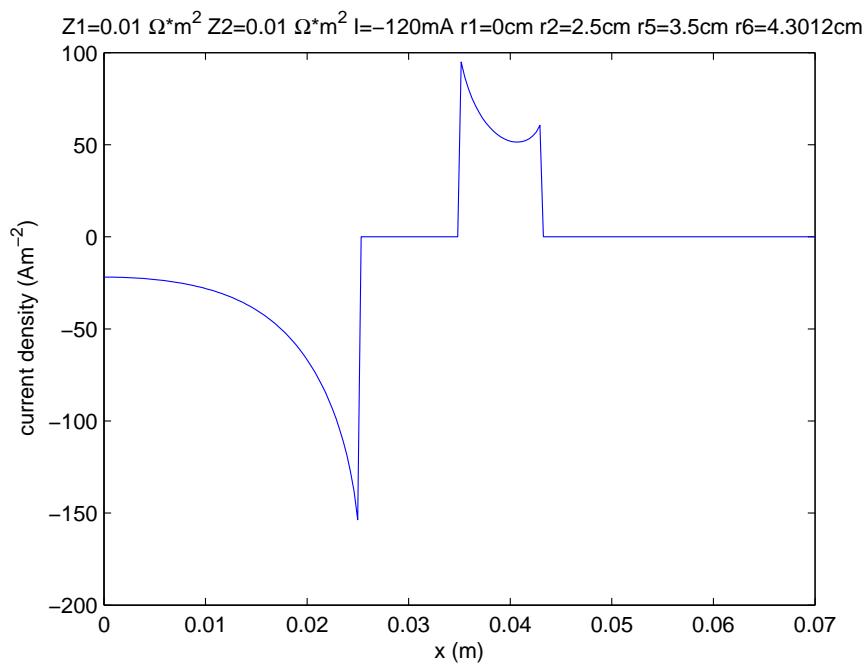


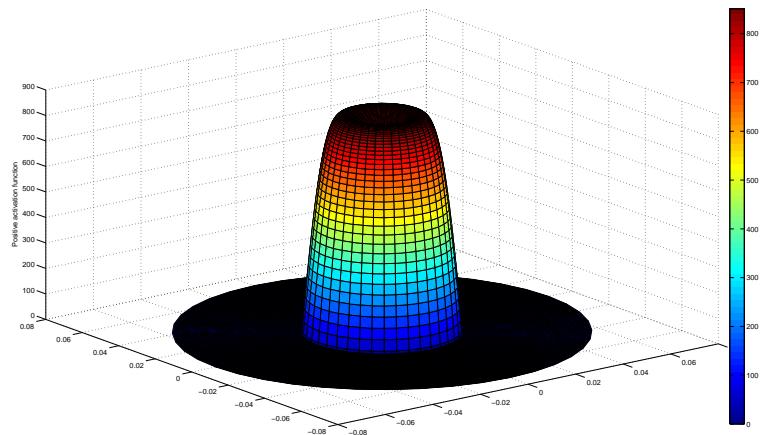
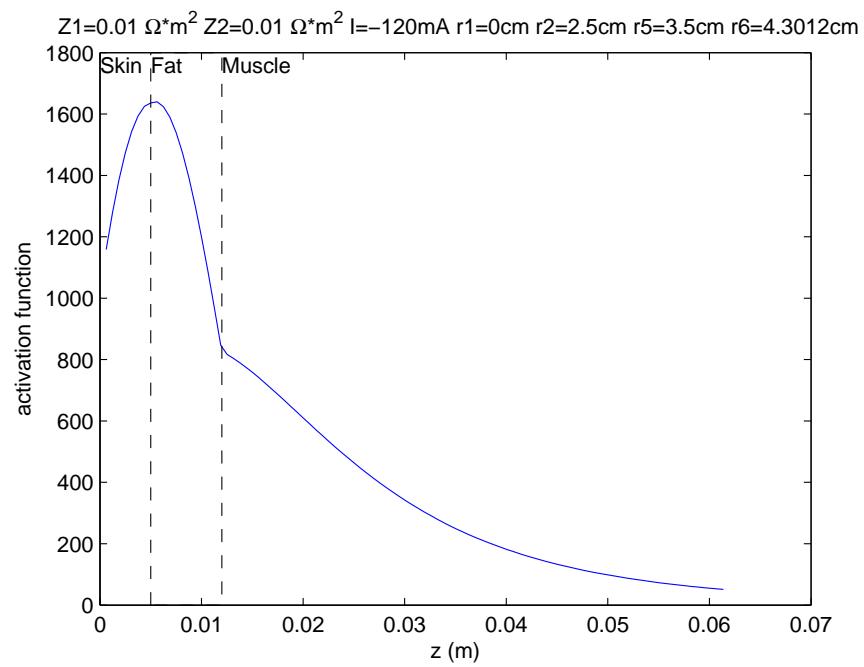
1.4.2 $Z_1=Z_2=0.01 \Omega\text{m}^2$



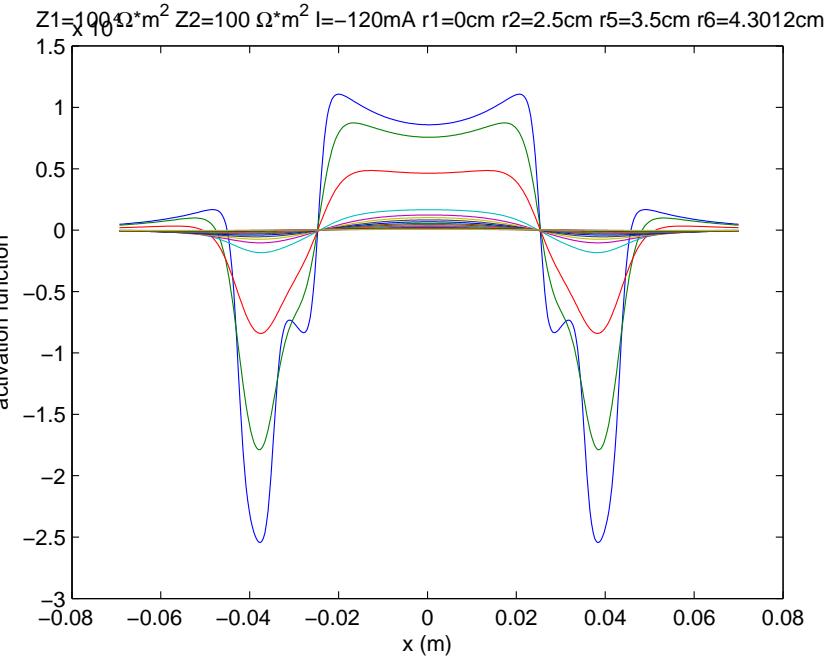
$Z1=0.01 \Omega\text{m}^2 Z2=0.01 \Omega\text{m}^2 I=-120\text{mA} r1=0\text{cm} r2=2.5\text{cm} r5=3.5\text{cm} r6=4.3012\text{cm} \text{depth}=15 \text{mm}$



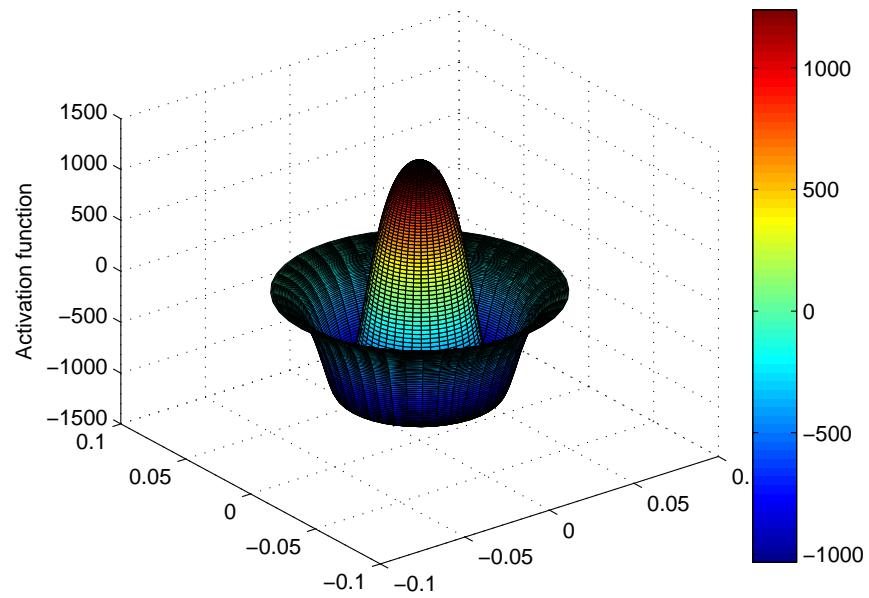


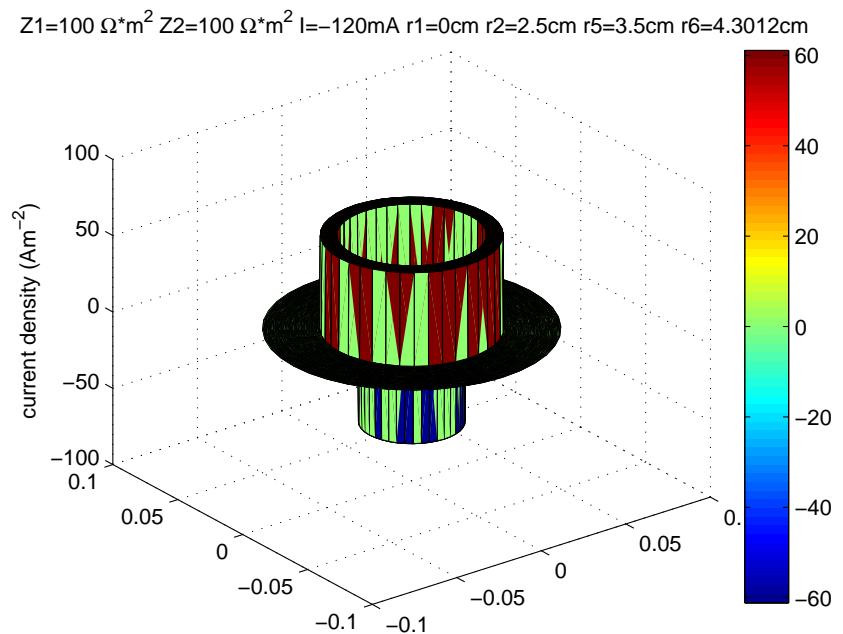
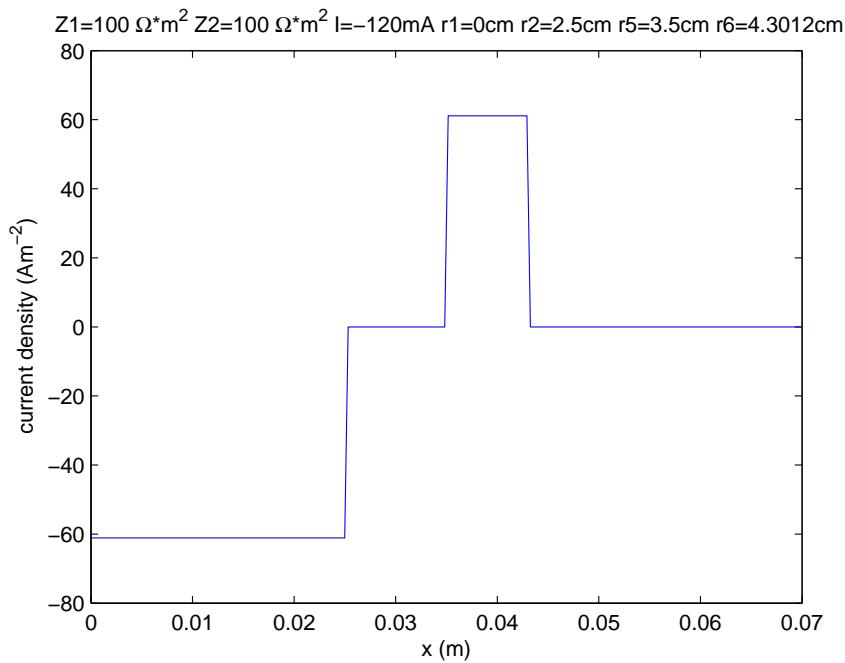


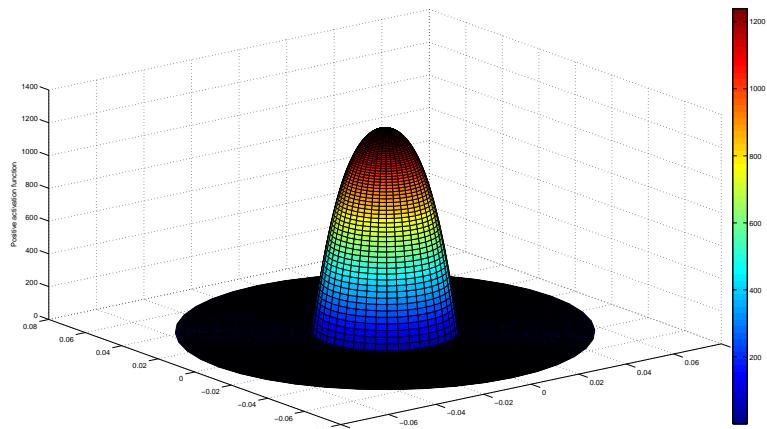
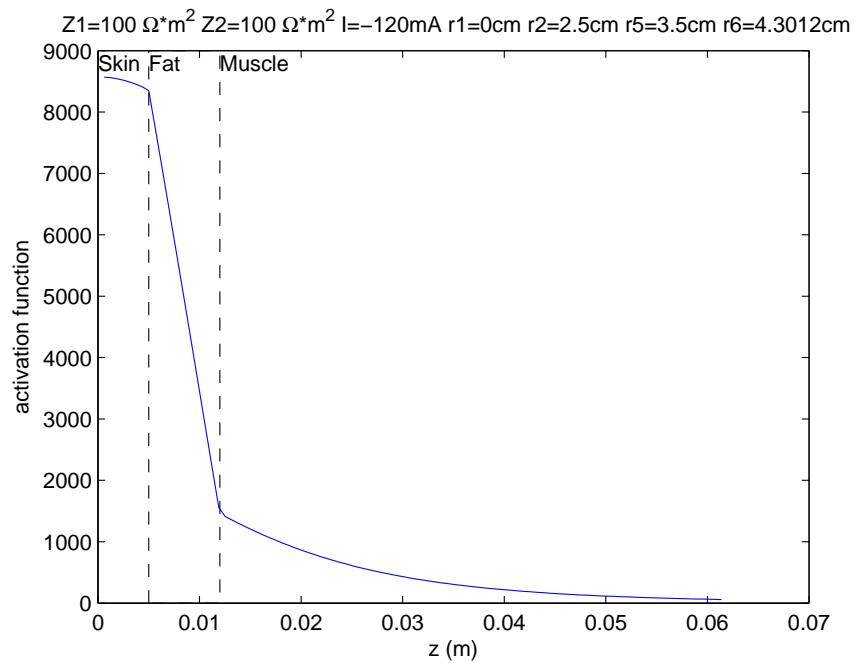
1.4.3 $Z_1=Z_2=100 \Omega\text{m}^2$



$100 \Omega\text{m}^2 Z2=100 \Omega\text{m}^2 I=-120\text{mA} r1=0\text{cm} r2=2.5\text{cm} r5=3.5\text{cm} r6=4.3012\text{cm depth}=15 \text{ mm}$

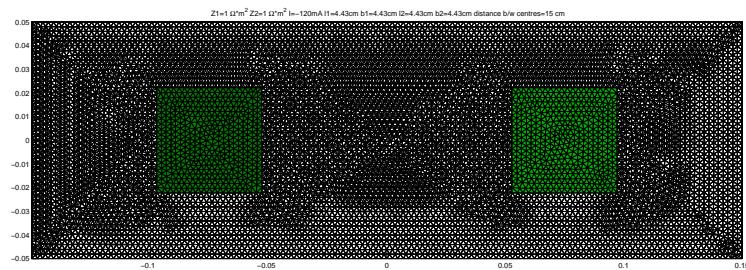






1.5

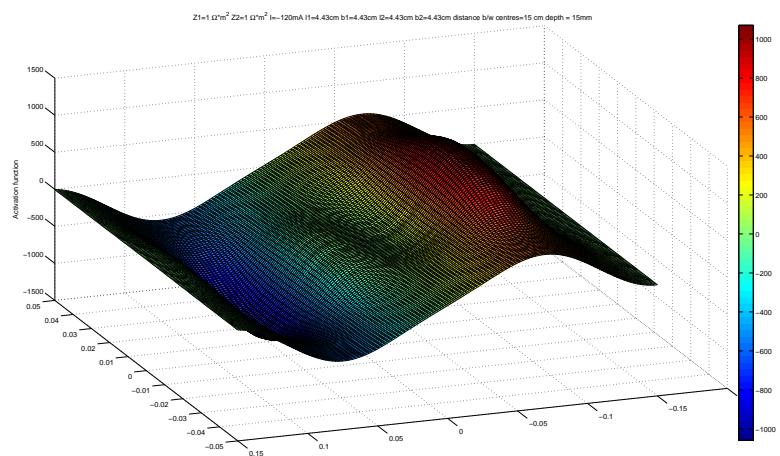
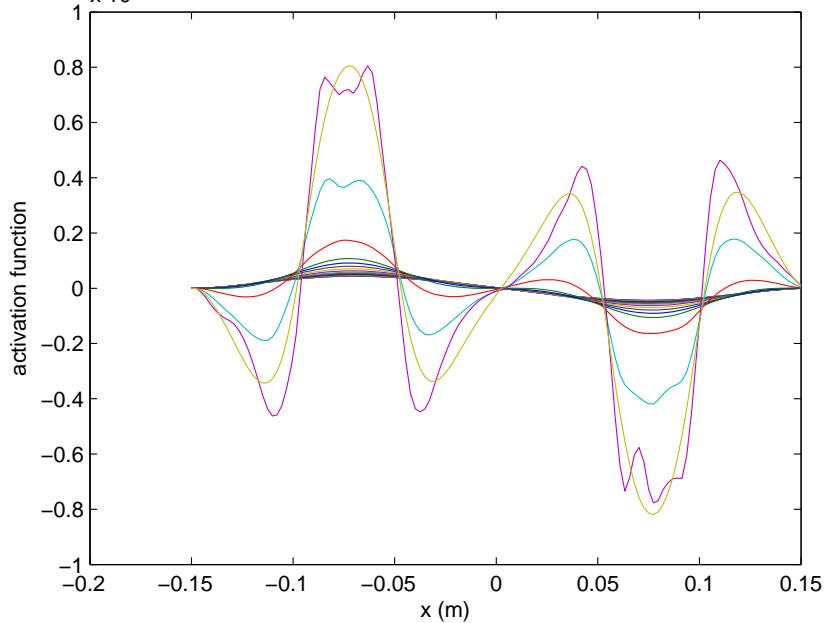
Side by side square electrodes with sides 4.43 cm each and distance between centres 15 cm -



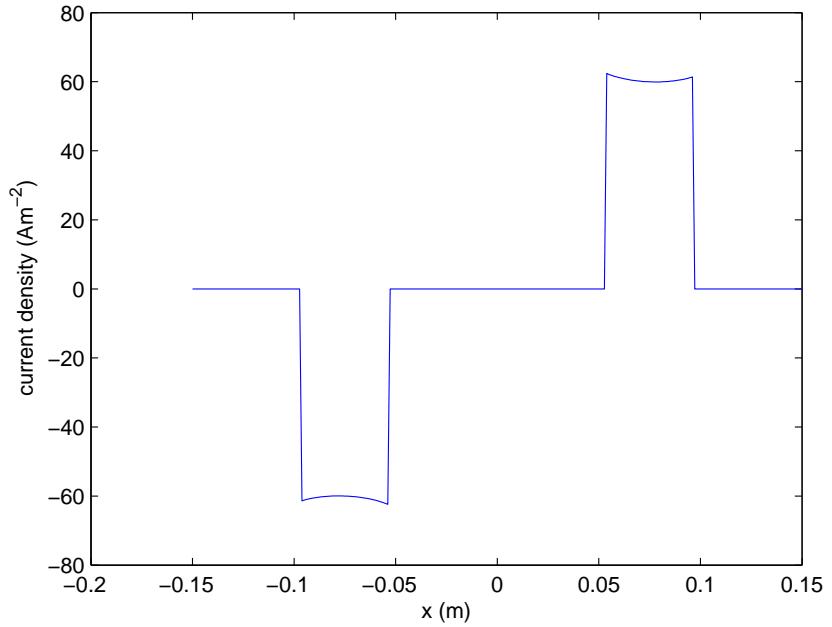
Parameters - $l_1 = b_1 = l_2 = b_2 = 4.43$ cm, distance b/w centres=15 cm, $I = 120$ mA, area=19.625 cm²

1.5.1 $Z_1=Z_2=1 \Omega m^2$

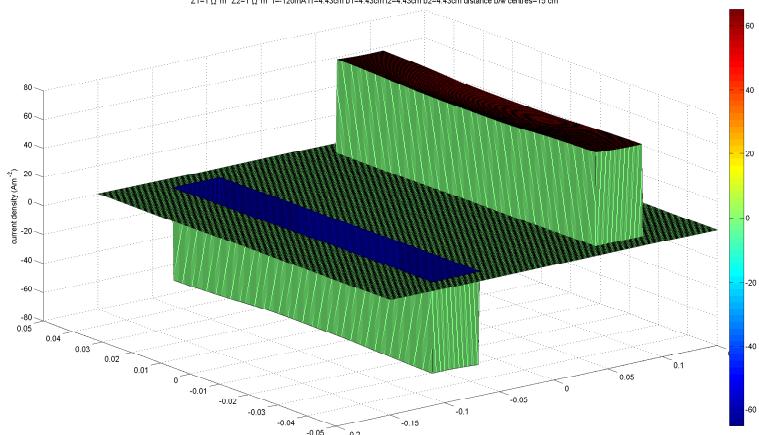
$\Omega^* m^2 Z2=1 \Omega^* m^2 I=-120mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w centre



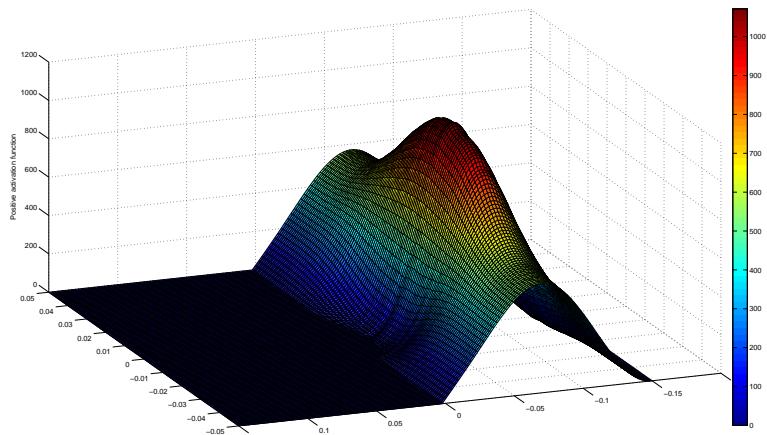
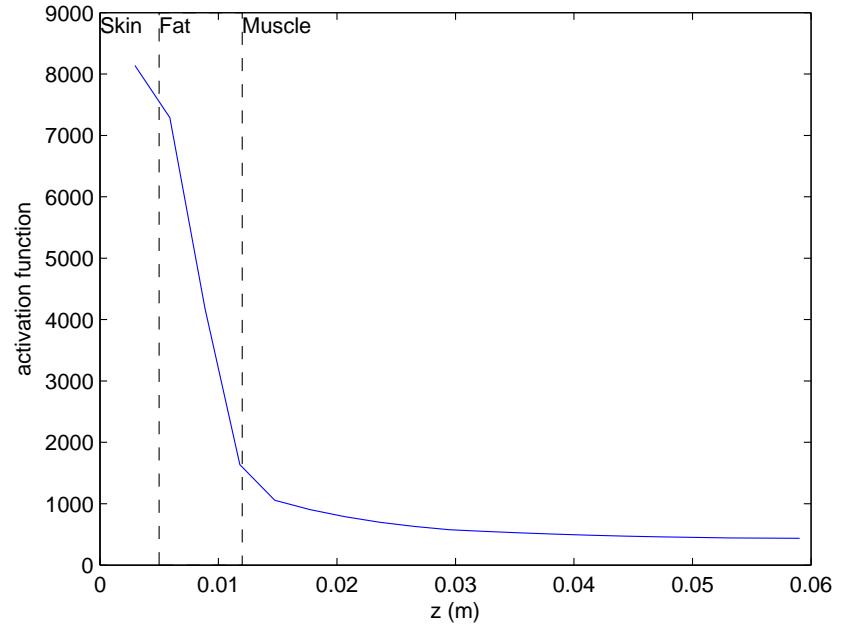
$\Omega^* m^2 Z2=1 \Omega^* m^2 I=-120mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w centre



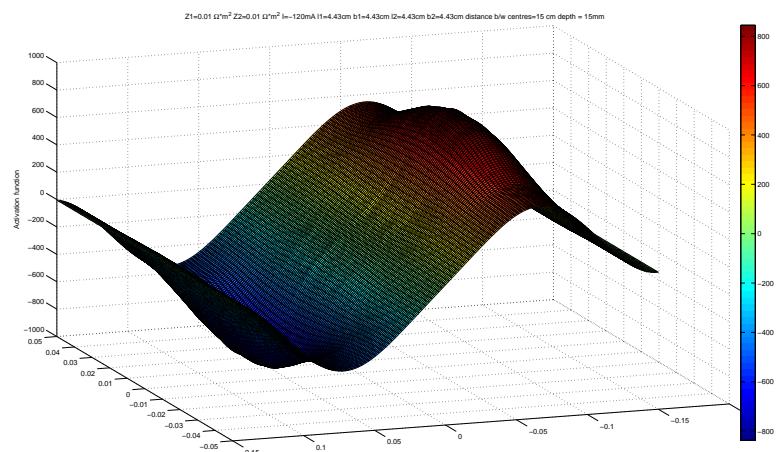
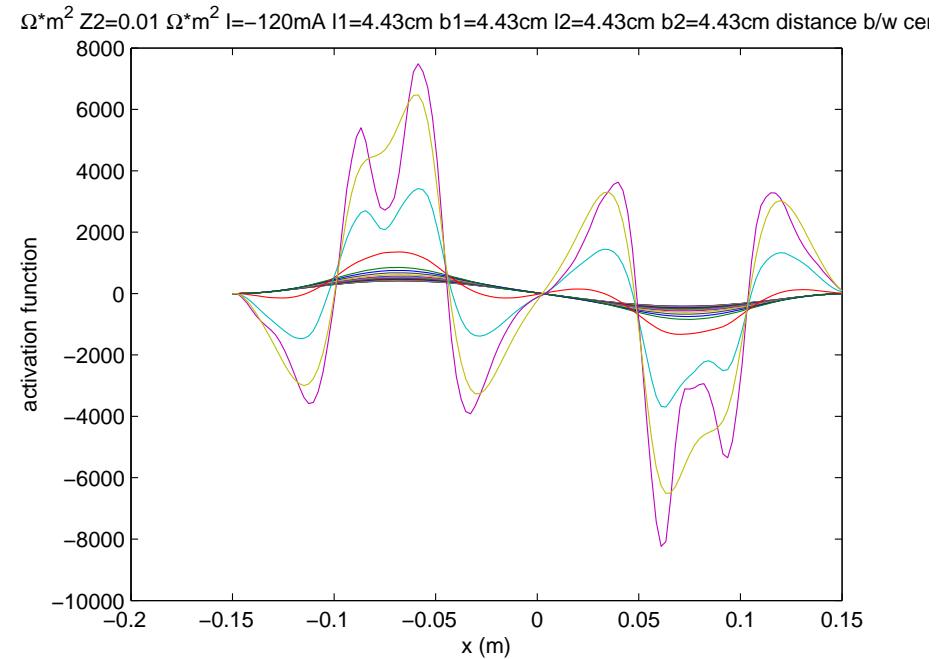
$Z1=1 \Omega^* m^2 Z2=1 \Omega^* m^2 I=-120mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w centres=15 cm



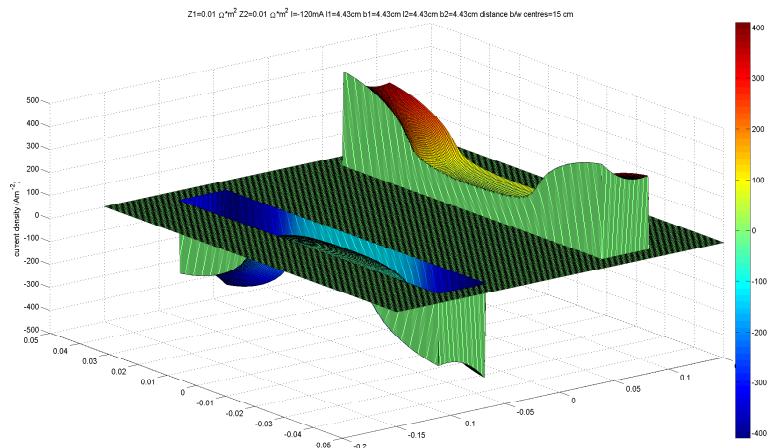
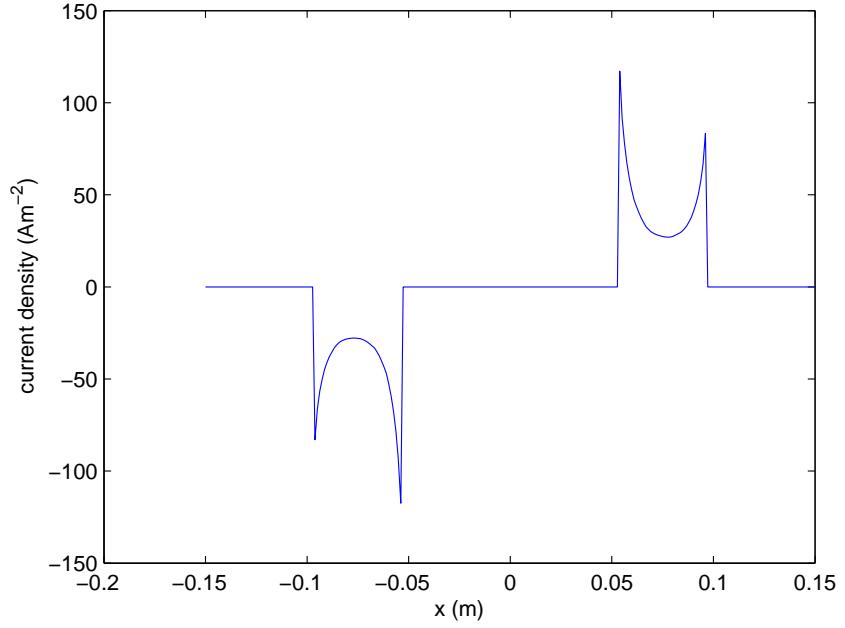
$$\Omega^* m^2 Z_2=1 \quad \Omega^* m^2 I=-120 \text{mA} \quad l_1=4.43\text{cm} \quad b_1=4.43\text{cm} \quad l_2=4.43\text{cm} \quad b_2=4.43\text{cm} \quad \text{distance b/w centre}$$



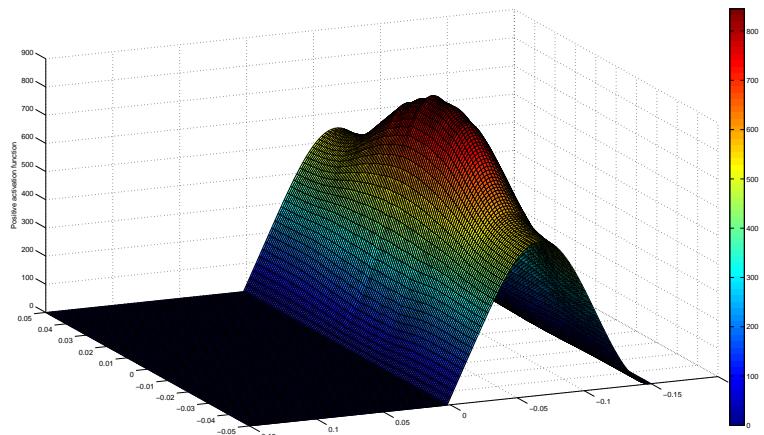
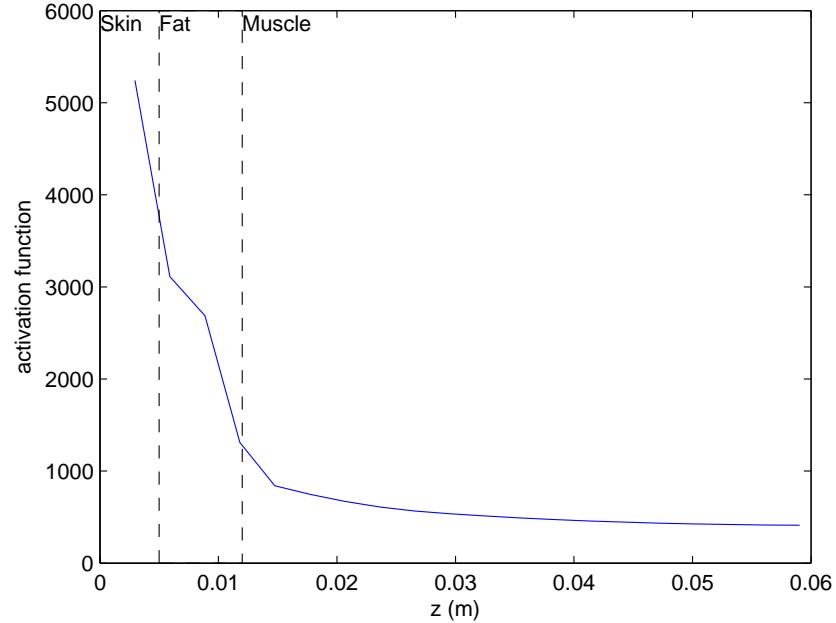
1.5.2 $Z_1=Z_2=0.01 \Omega m^2$



$\Omega^* m^2 Z2=0.01 \Omega^* m^2 I=-120mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w centres=15 cm

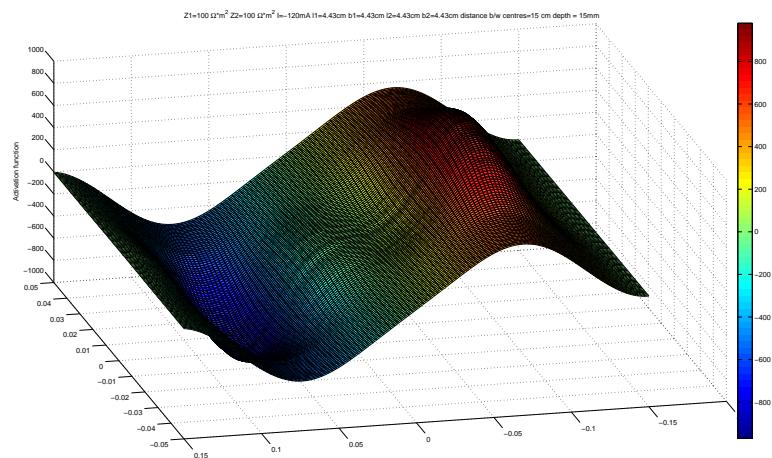
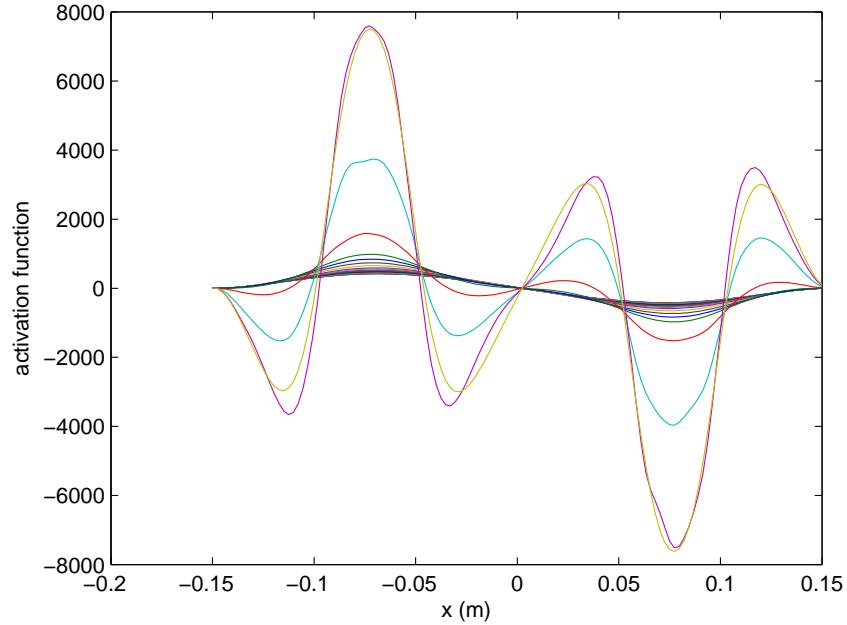


$$\Omega^* m^2 Z_2 = 0.01 \quad \Omega^* m^2 I = -120 \text{mA} \quad l_1 = 4.43 \text{cm} \quad b_1 = 4.43 \text{cm} \quad l_2 = 4.43 \text{cm} \quad b_2 = 4.43 \text{cm} \quad \text{distance b/w centers} = 10 \text{cm}$$

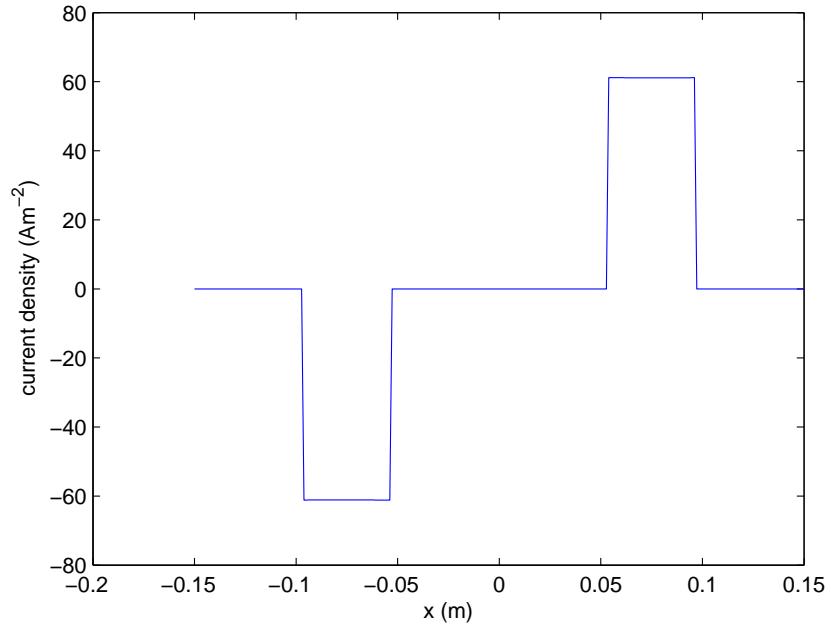


1.5.3 $Z_1=Z_2=100 \Omega\text{m}^2$

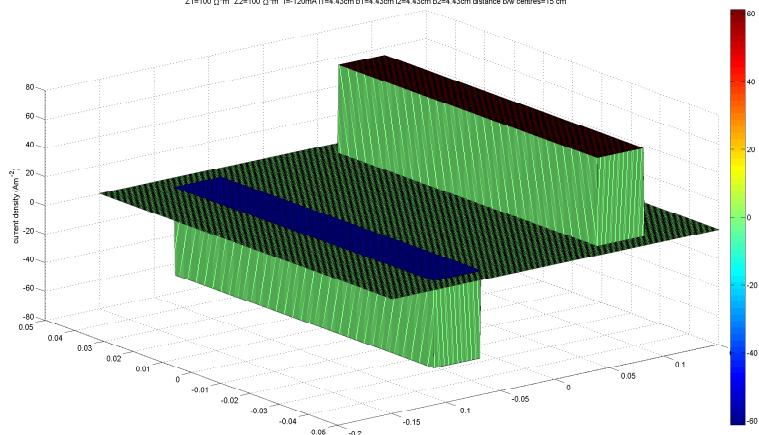
$| \Omega^2 m^2 Z_2=100 \Omega^2 m^2 | = -120 \text{mA} I_1=4.43 \text{cm} b_1=4.43 \text{cm} I_2=4.43 \text{cm} b_2=4.43 \text{cm}$ distance b/w cer

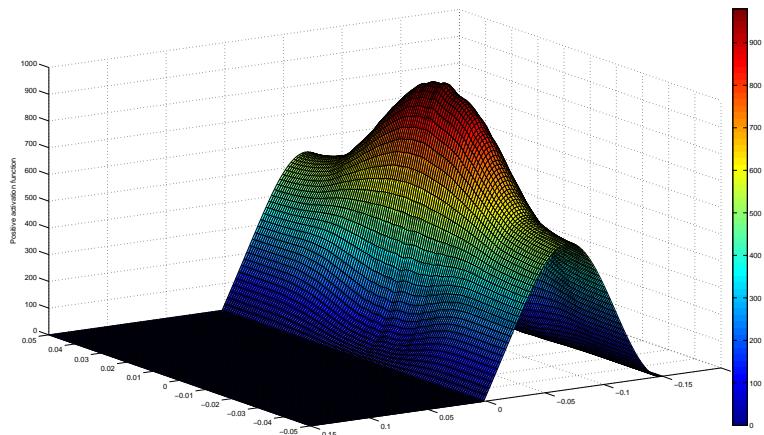
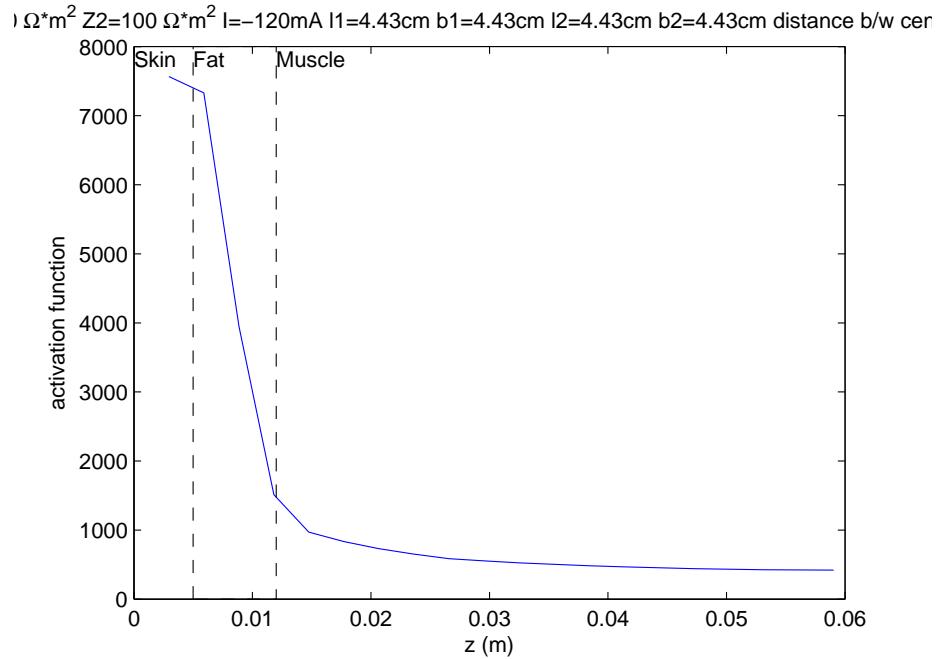


$\Omega^2 m^2 Z_1=100 \Omega^2 m^2 Z_2=100 I=-120 \text{mA} l_1=4.43 \text{cm} b_1=4.43 \text{cm} l_2=4.43 \text{cm} b_2=4.43 \text{cm}$ distance b/w cer



$Z_1=100 \Omega^2 m^2 Z_2=100 \Omega^2 m^2 I=-120 \text{mA} l_1=4.43 \text{cm} b_1=4.43 \text{cm} l_2=4.43 \text{cm} b_2=4.43 \text{cm}$ distance b/w centres=15 cm

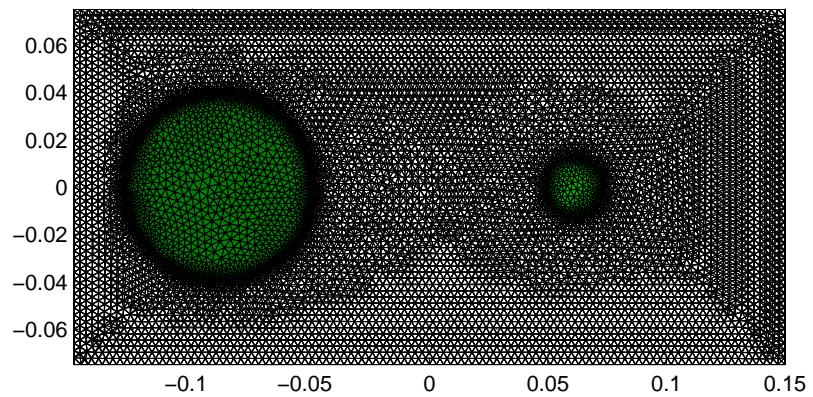




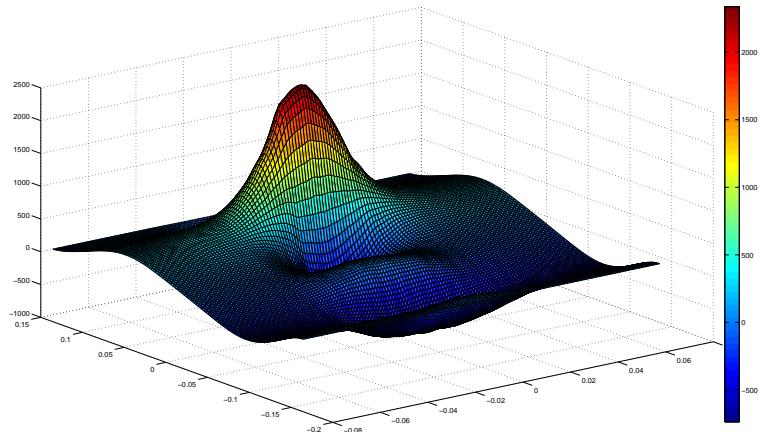
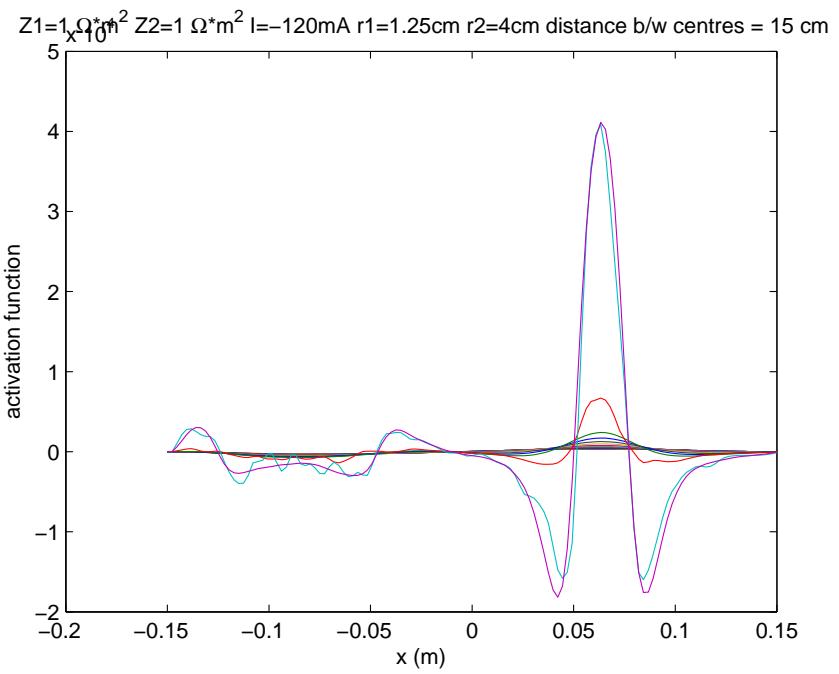
1.6

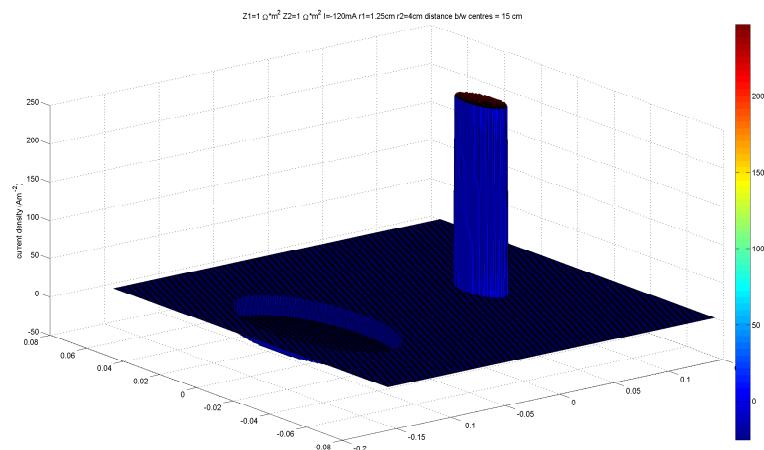
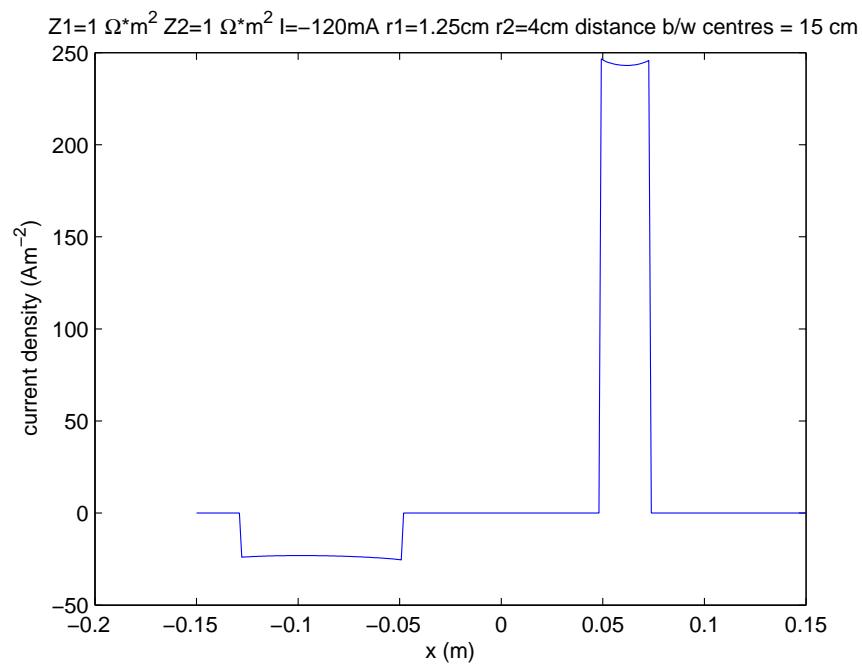
One small circular disk (active) 2.5 cm diameter. Second circular electrode (indifferent) 8cm diameter. Separation 15cm centre to centre.

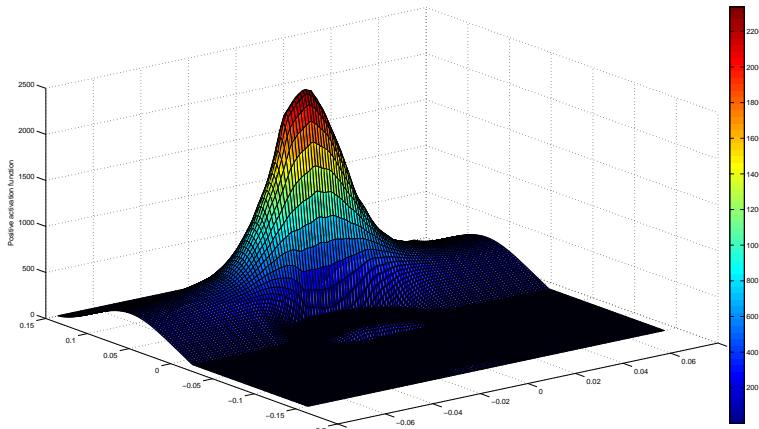
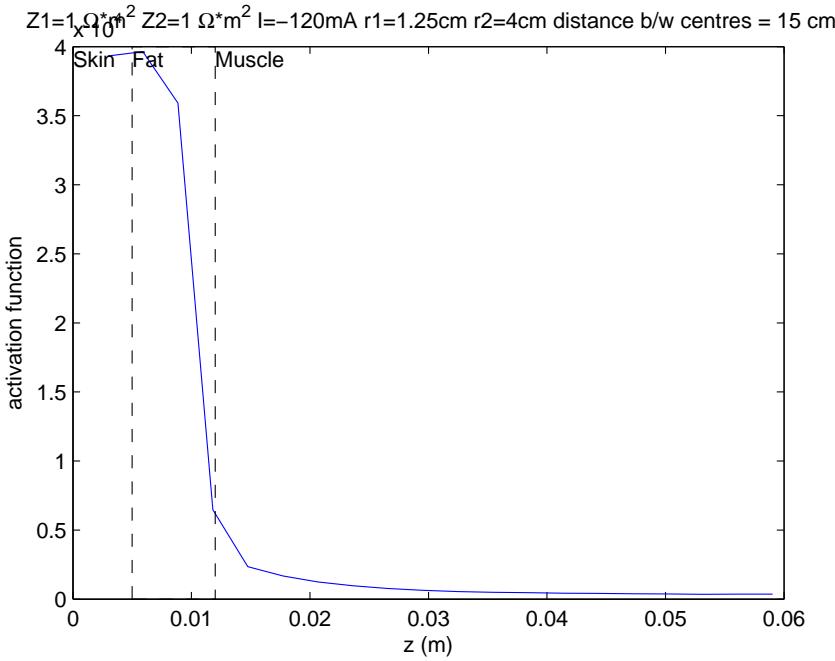
$Z_1=1 \Omega \cdot m^2$ $Z_2=1 \Omega \cdot m^2$ $I=-120mA$ $r_1=1.25cm$ $r_2=4cm$ distance b/w centres = 15 cm



Parameters - active electrode - $r_1=1.25$ cm, area= 4.9087 cm^2 , indifferent electrode - $r_2=4.0$ cm, area= 50.2655 cm^2 , distance b/w centres=15 cm, $Z_1=Z_2=1 \Omega \cdot m^2$, $I=120$ mA







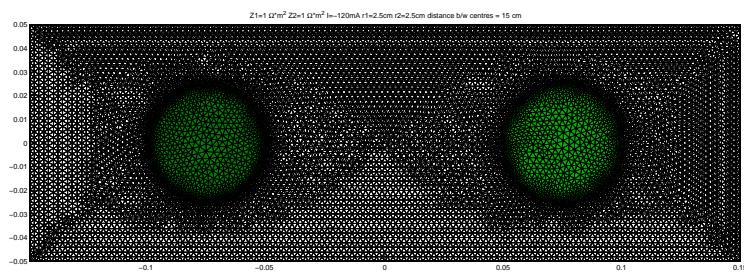
2 Simulations with maximum surface current density 61.12 Am^{-2}

Since high surface current density can lead to burns, keeping the maximum current density constant is a useful way to compare different configurations and contact impedances. The value chosen (61.12 Am^{-2}) is the current density

corresponding to 120 mA current injected into a disk of radius 2.5 cm assuming constant current density in the skin underneath the electrode.

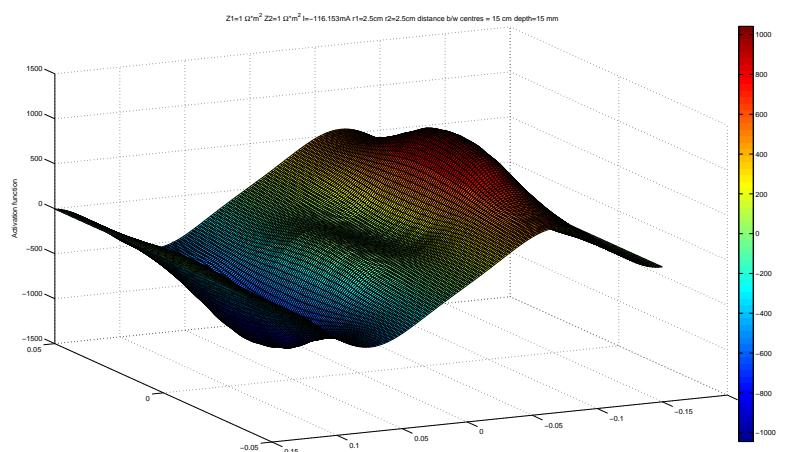
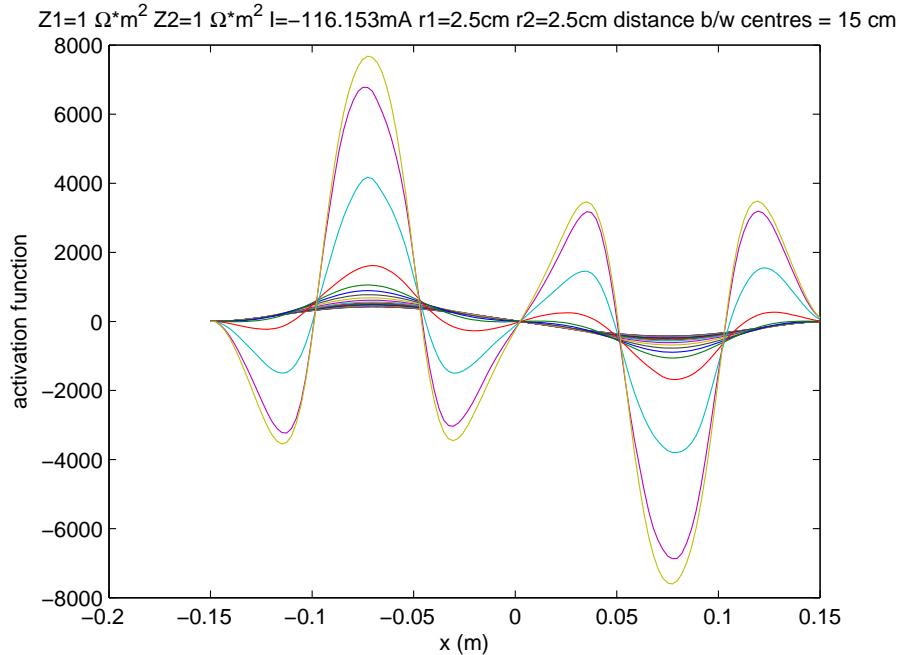
2.1

Side by side disk electrodes with radii 2.5 cm each and distance between centres 15 cm -

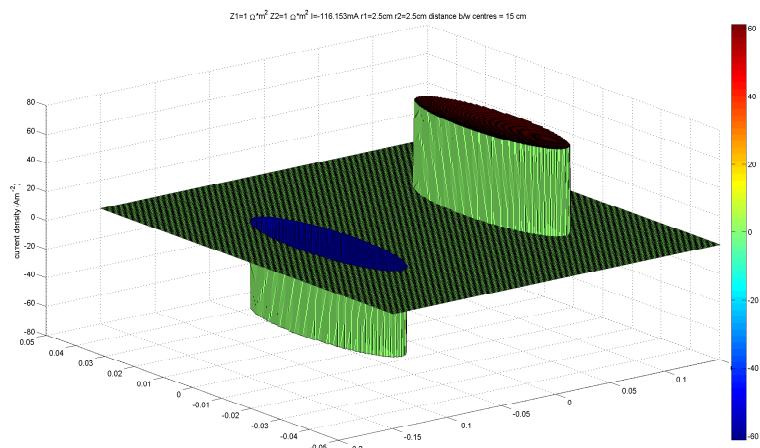
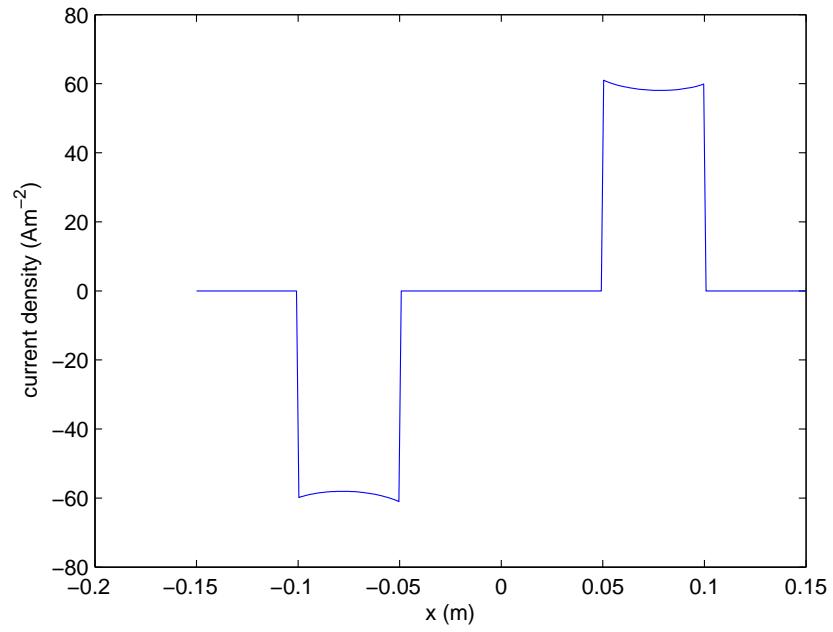


Parameters - $r_1=r_2=2.5$ cm, distance b/w centres=15 cm, area=19.635 cm^2

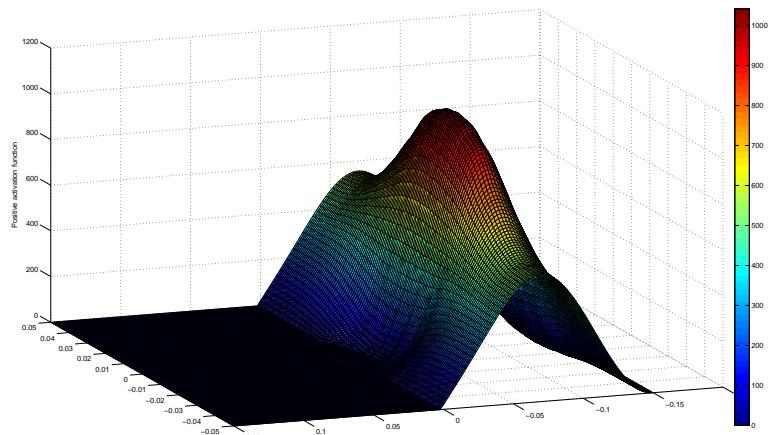
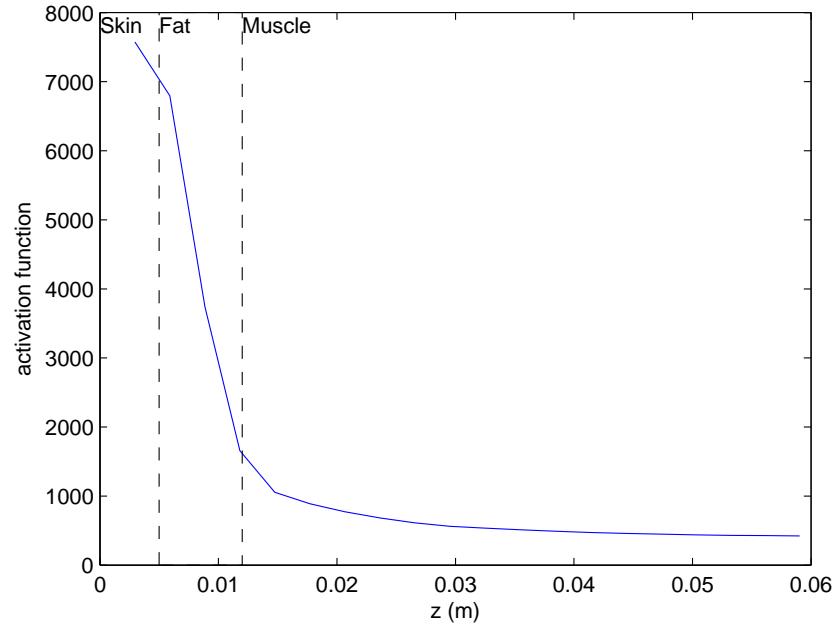
2.1.1 $Z_1=Z_2=1 \Omega\text{m}^2$, $I=116.153 \text{ mA}$



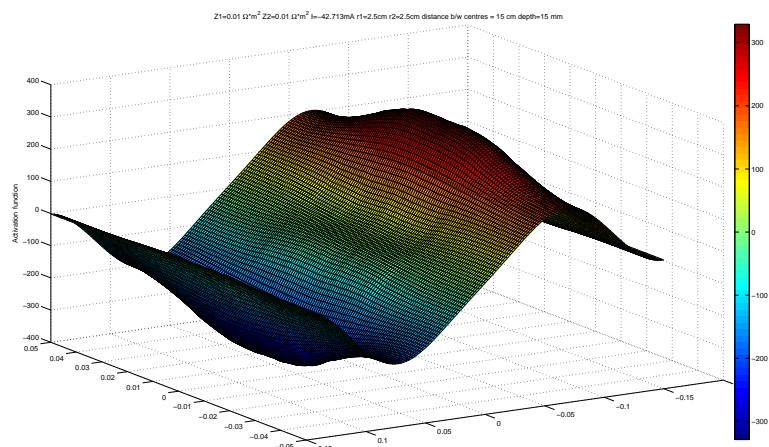
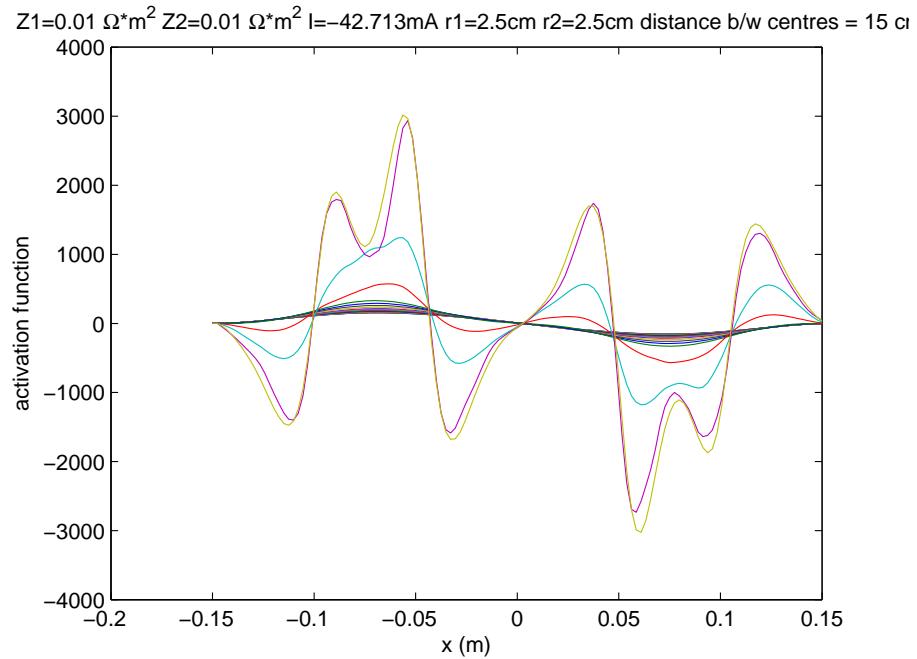
$Z_1=1 \Omega \cdot m^2$ $Z_2=1 \Omega \cdot m^2$ $I=-116.153mA$ $r_1=2.5cm$ $r_2=2.5cm$ distance b/w centres = 15 cm

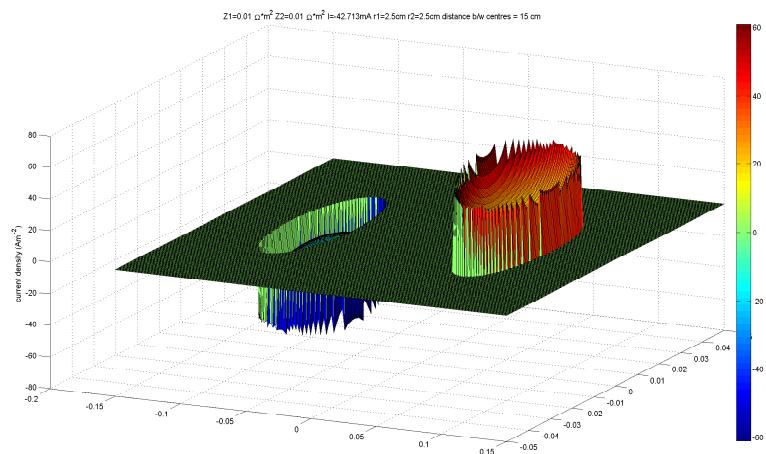
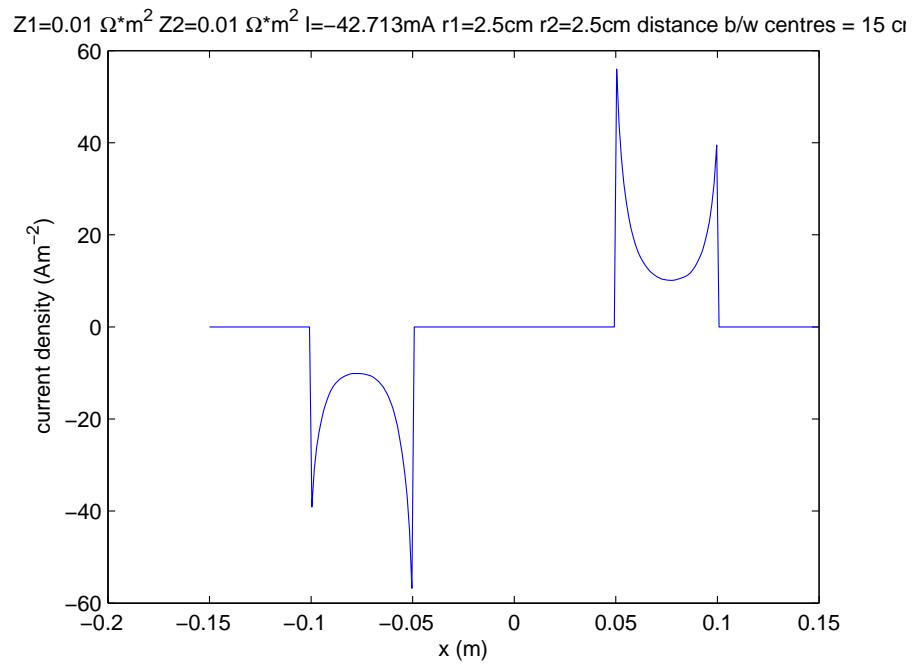


$Z_1=1 \Omega \cdot m^2$ $Z_2=1 \Omega \cdot m^2$ $I=-116.153mA$ $r_1=2.5cm$ $r_2=2.5cm$ distance b/w centres = 15 cm

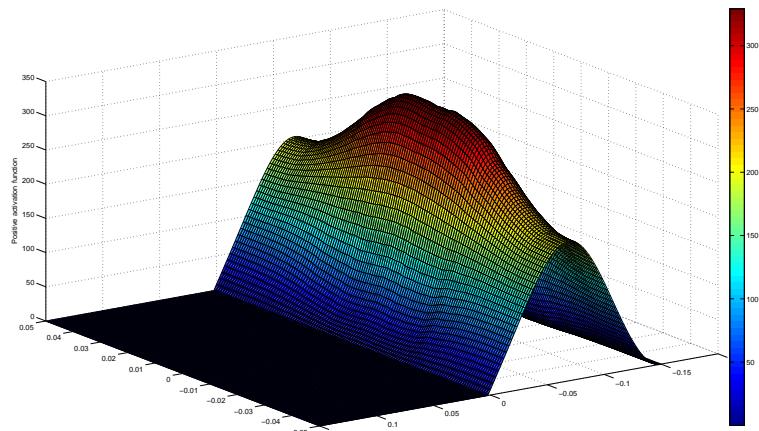
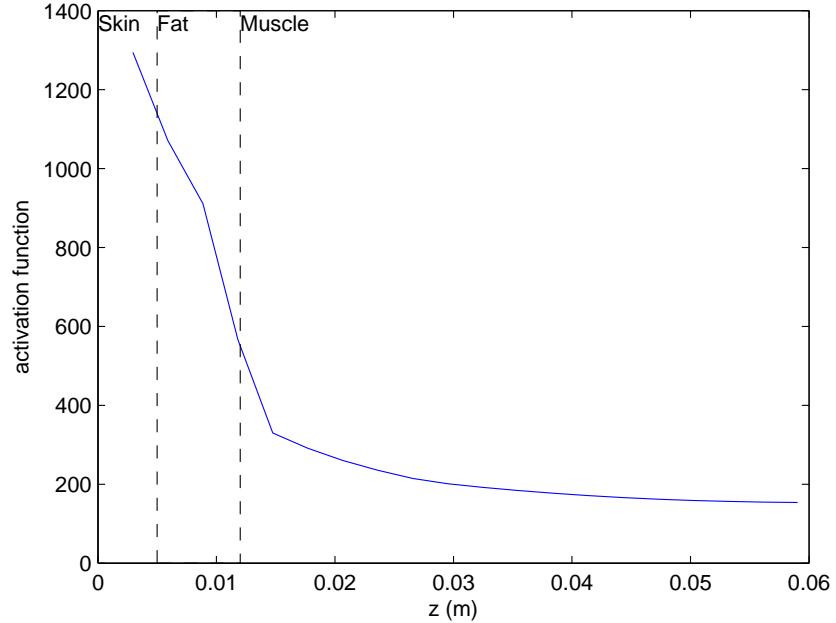


2.1.2 $Z_1=Z_2=0.01 \Omega \cdot m^2$, $I=42.713 \text{ mA}$





$Z_1=0.01 \Omega \cdot m^2$ $Z_2=0.01 \Omega \cdot m^2$ $I=-42.713mA$ $r_1=2.5cm$ $r_2=2.5cm$ distance b/w centres = 15 cm



2.1.3 $Z_1=Z_2=100 \Omega \cdot m^2$, $I=120 \text{ mA}$

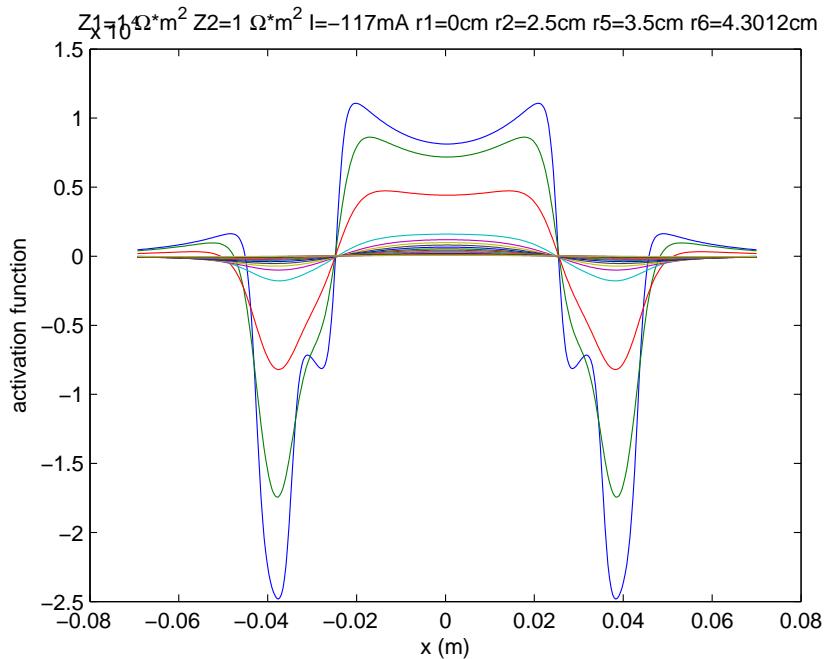
In this case the current density is almost constant and hence this is the same as injecting 120 mA of current.

2.2

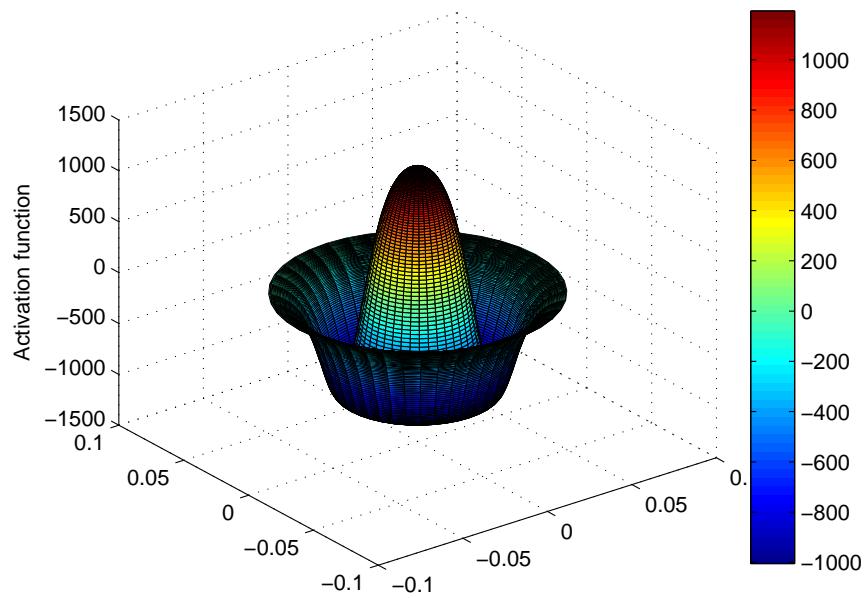
Concentric disk and ring electrodes. Parameters -

Inner electrode: $r_1=0$ cm, $r_2=2.5$ cm, area= 19.635 cm^2 , Outer electrode:
 $r_5=3.5$ cm, $r_6=4.3012$ cm, area= 19.635 cm^2

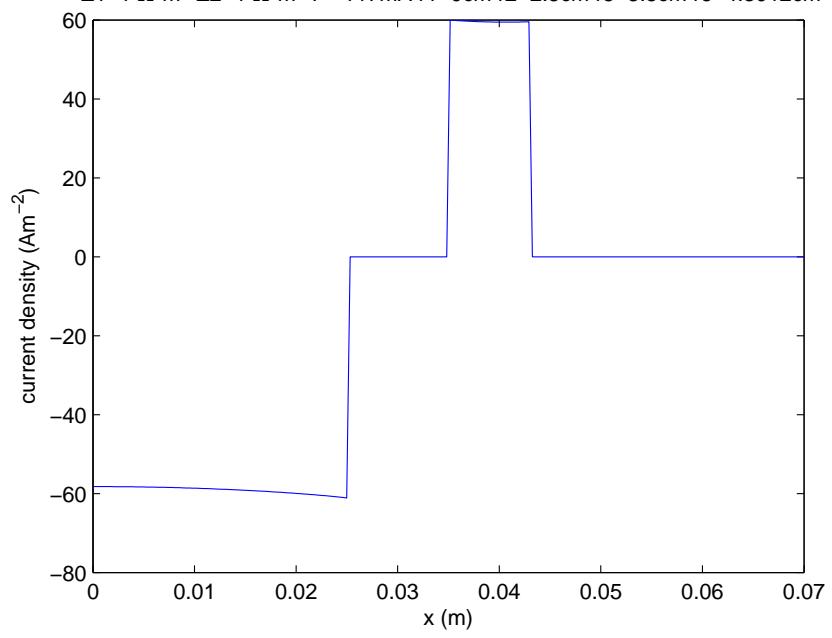
2.2.1 $Z_1=Z_2=1 \Omega\text{m}^2$, $I=117 \text{ mA}$



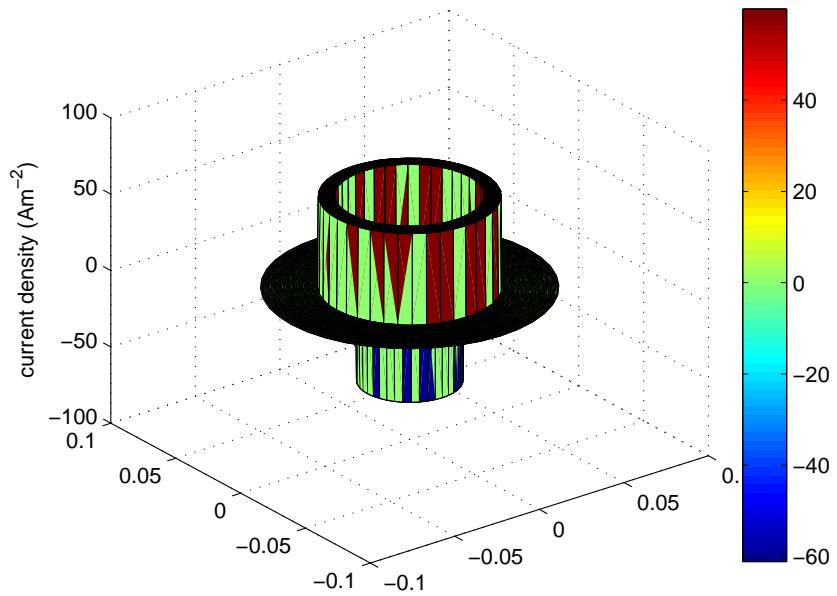
$=1 \Omega^*m^2 Z2=1 \Omega^*m^2 I=-117mA r1=0cm r2=2.5cm r5=3.5cm r6=4.3012cm$ depth = 15 mm



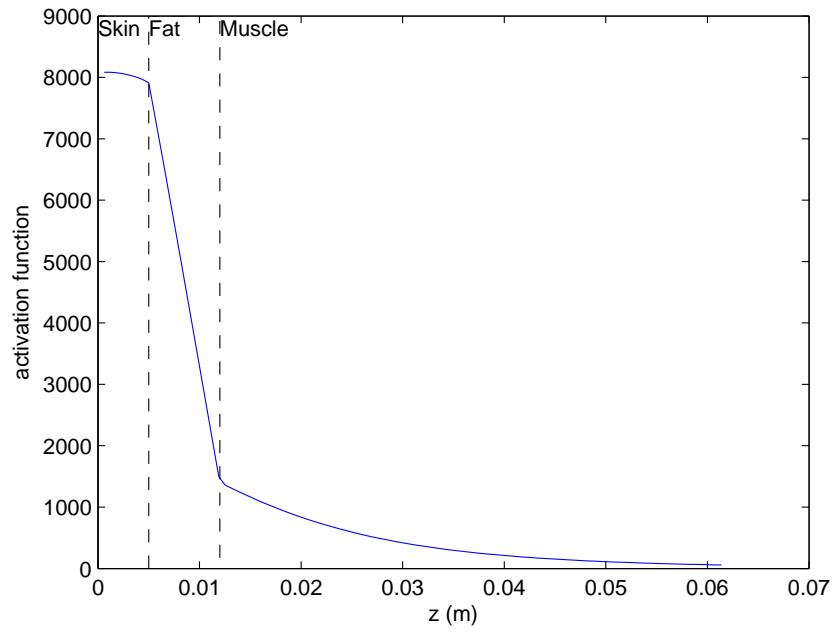
$Z1=1 \Omega^*m^2 Z2=1 \Omega^*m^2 I=-117mA r1=0cm r2=2.5cm r5=3.5cm r6=4.3012cm$

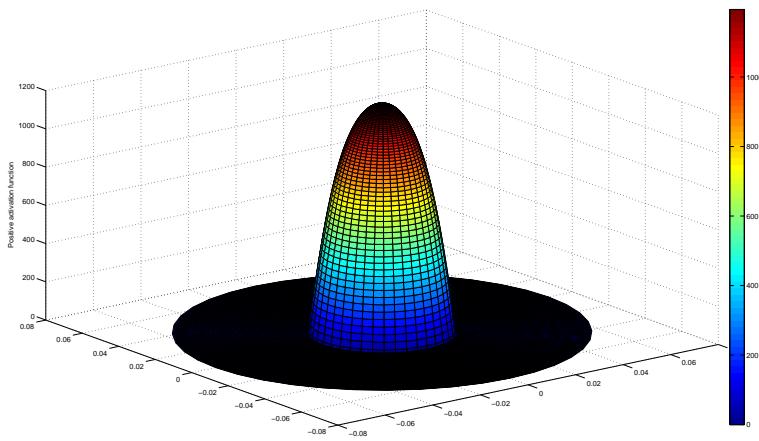


$$Z1=1 \Omega \cdot m^2 \quad Z2=1 \Omega \cdot m^2 \quad I=-117mA \quad r1=0cm \quad r2=2.5cm \quad r5=3.5cm \quad r6=4.3012cm$$

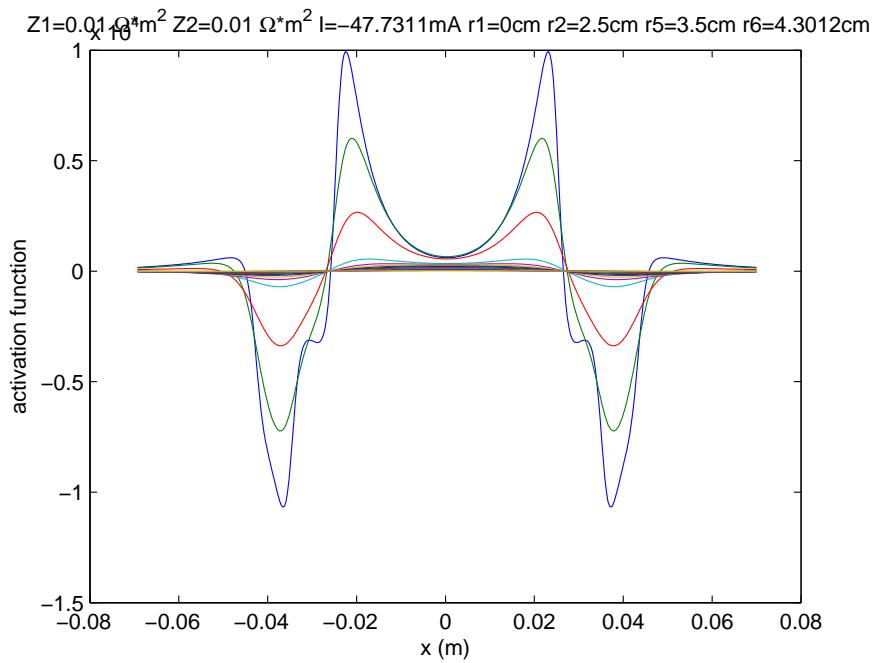


$$Z1=1 \Omega \cdot m^2 \quad Z2=1 \Omega \cdot m^2 \quad I=-117mA \quad r1=0cm \quad r2=2.5cm \quad r5=3.5cm \quad r6=4.3012cm$$

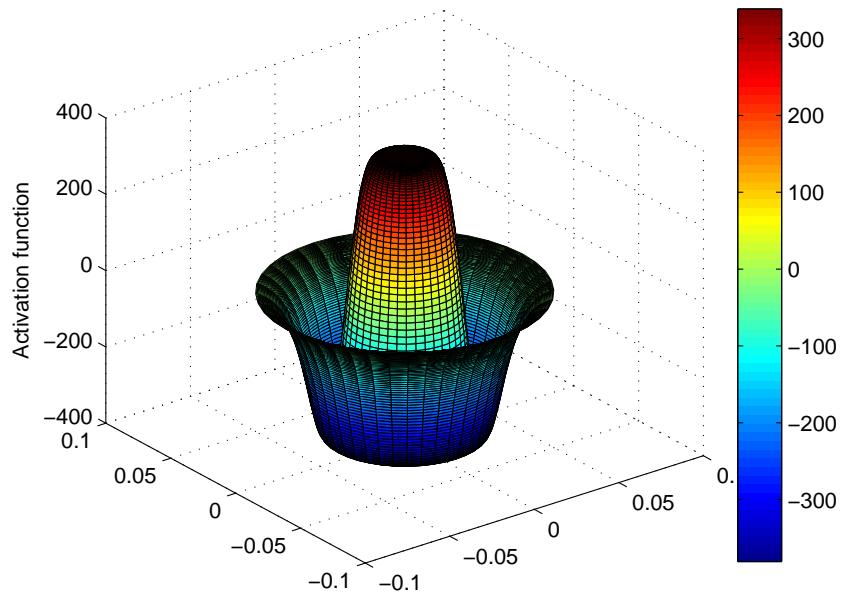




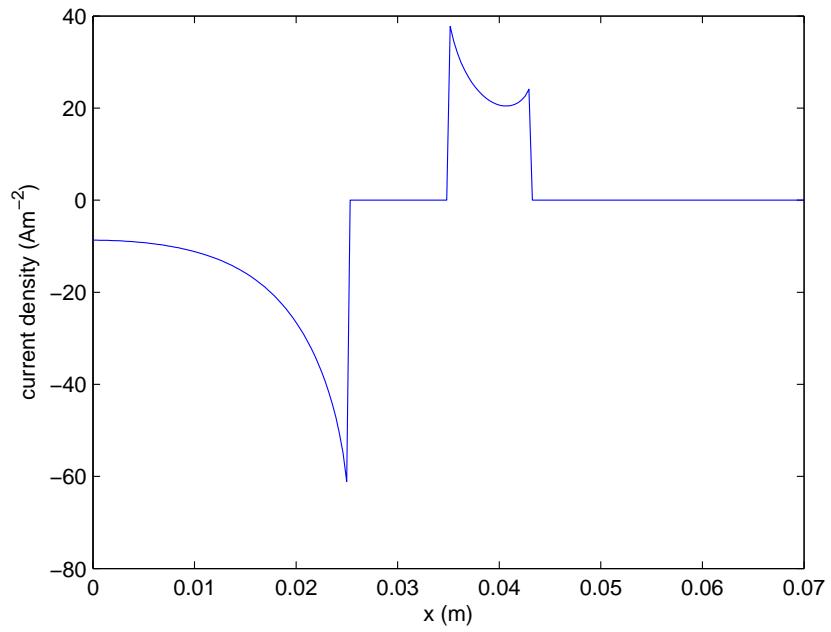
2.2.2 $Z_1=Z_2=0.01 \Omega\text{m}^2$, $I=47.7311 \text{ mA}$



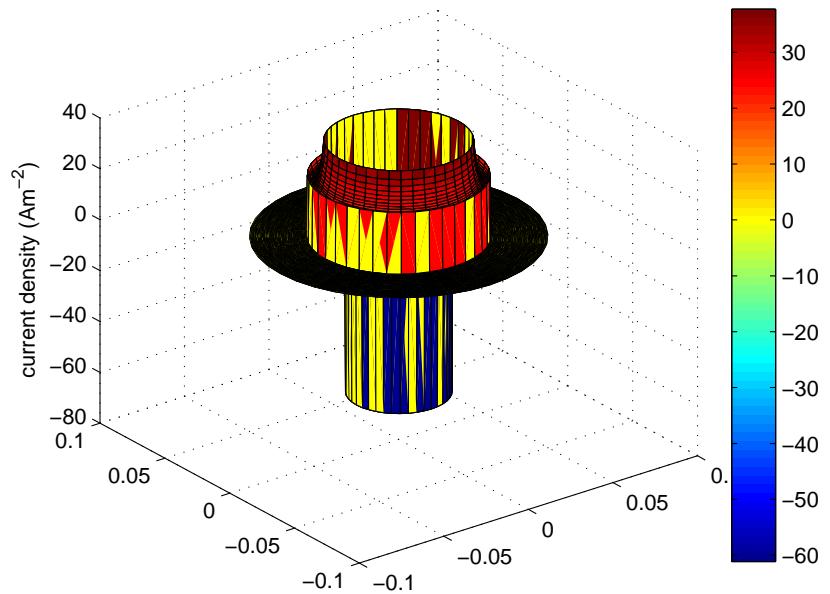
$Z_1 = 0.01 \Omega \cdot m^2$ $Z_2 = 0.01 \Omega \cdot m^2$ $I = -47.7311 \text{ mA}$ $r_1 = 0 \text{ cm}$ $r_2 = 2.5 \text{ cm}$ $r_5 = 3.5 \text{ cm}$ $r_6 = 4.3012 \text{ cm}$ depth = 15 mm



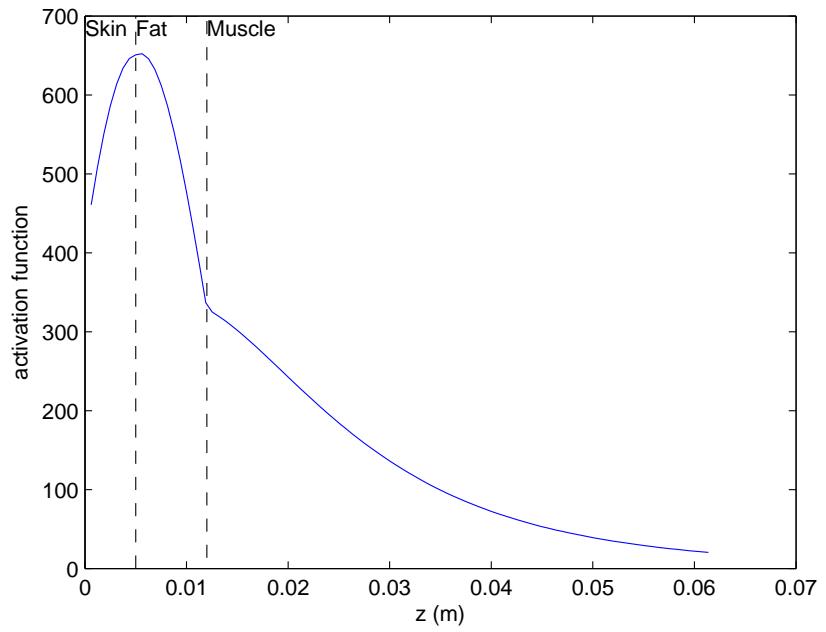
$Z_1 = 0.01 \Omega \cdot m^2$ $Z_2 = 0.01 \Omega \cdot m^2$ $I = -47.7311 \text{ mA}$ $r_1 = 0 \text{ cm}$ $r_2 = 2.5 \text{ cm}$ $r_5 = 3.5 \text{ cm}$ $r_6 = 4.3012 \text{ cm}$

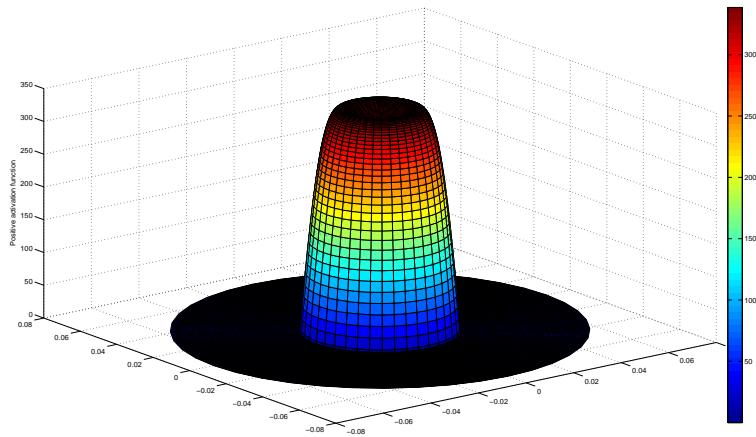


$$Z_1=0.01 \Omega \cdot m^2 \quad Z_2=0.01 \Omega \cdot m^2 \quad I=-47.7311mA \quad r_1=0cm \quad r_2=2.5cm \quad r_5=3.5cm \quad r_6=4.3012cm$$



$$Z_1=0.01 \Omega \cdot m^2 \quad Z_2=0.01 \Omega \cdot m^2 \quad I=-47.7311mA \quad r_1=0cm \quad r_2=2.5cm \quad r_5=3.5cm \quad r_6=4.3012cm$$



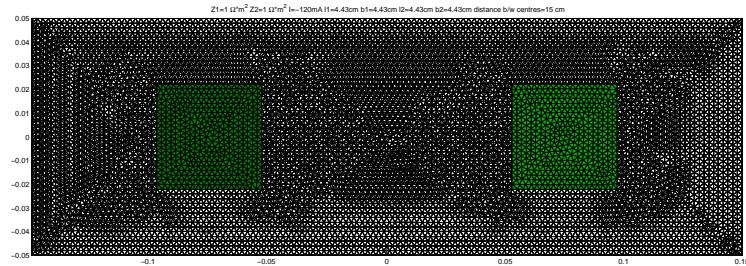


2.2.3 $Z_1=Z_2=100 \Omega\text{m}^2$, $I=120 \text{ mA}$

In this case the current density is almost constant and hence this is the same as injecting 120 mA of current.

2.3

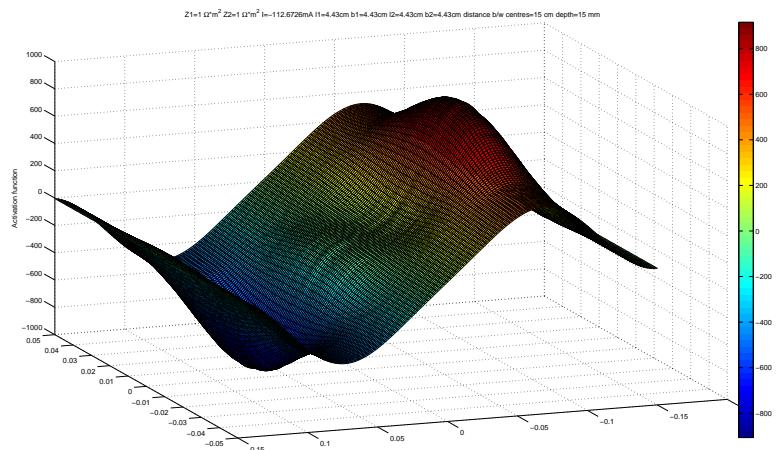
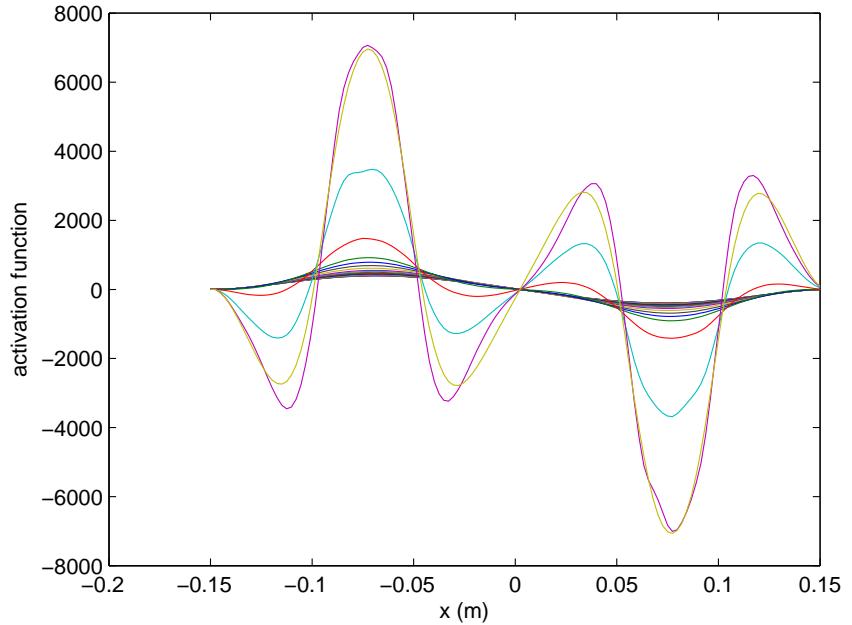
Side by side square electrodes with sides 4.43 cm each and distance between centres 15 cm -



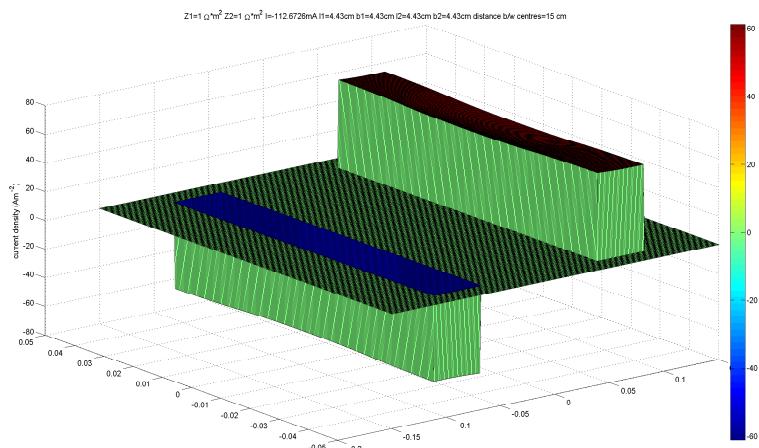
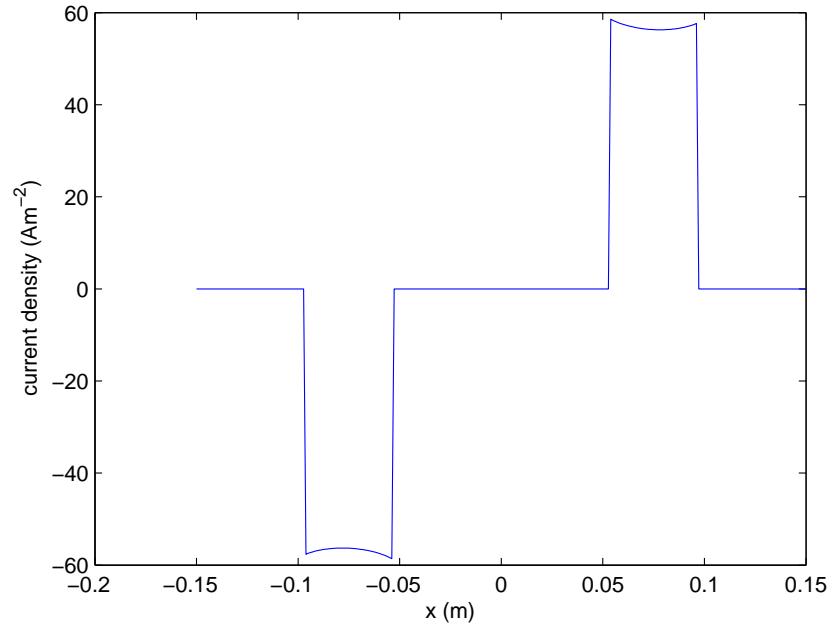
Parameters - $l_1=b_1=l_2=b_2=4.43 \text{ cm}$, distance b/w centres=15 cm, area=19.625 cm^2

2.3.1 $Z_1=Z_2=1 \Omega m^2$, $I=112.673$ mA

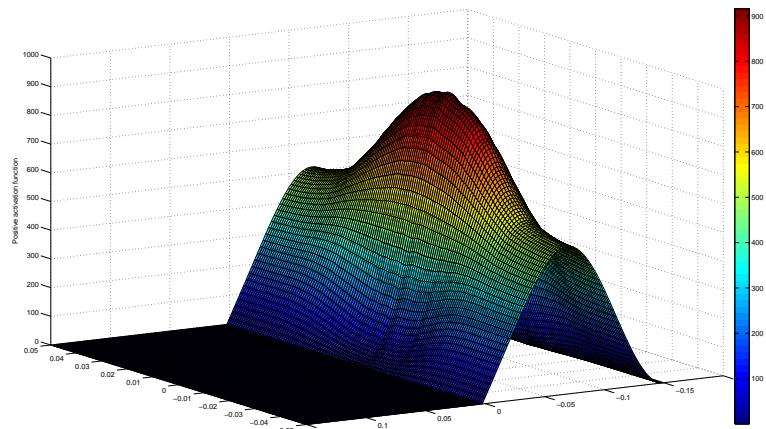
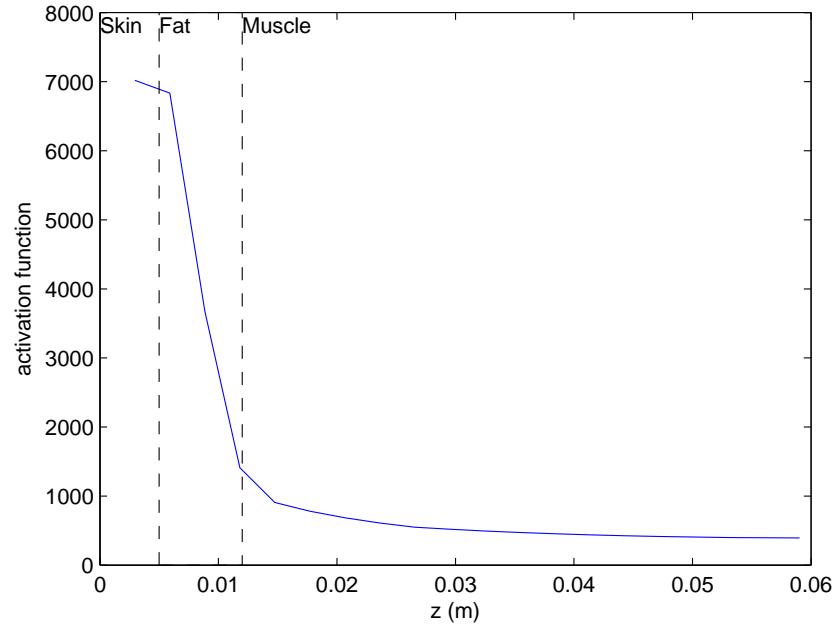
$*m^2 Z2=1 \Omega*m^2 I=-112.6726mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w cer



$*m^2 Z2=1 \Omega*m^2 I=-112.6726mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w cer

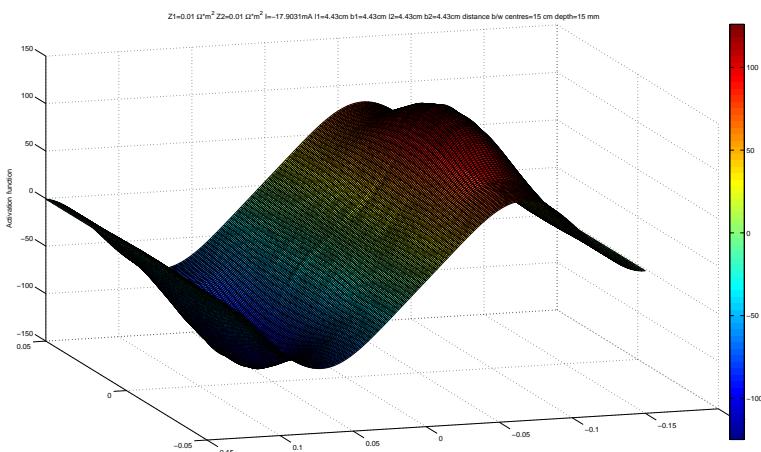
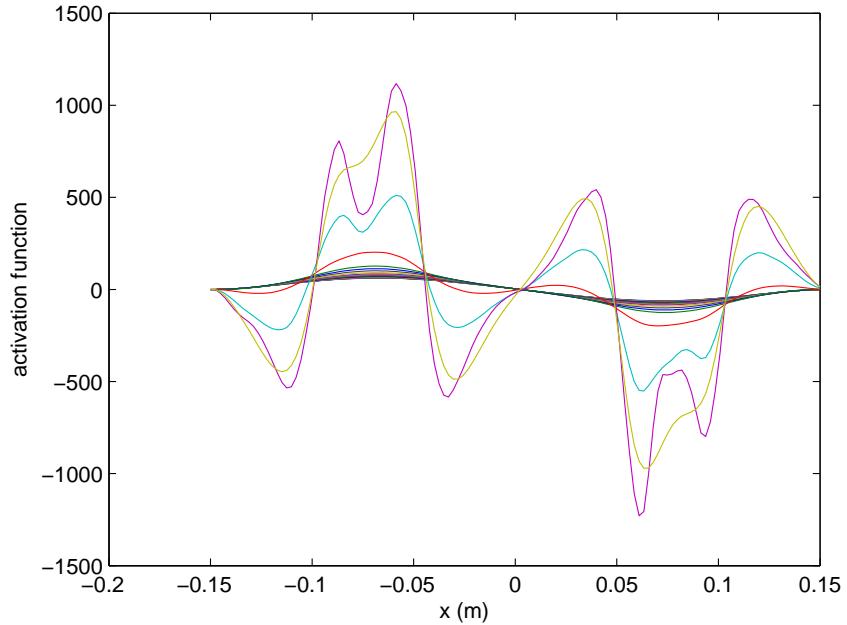


$*m^2 Z2=1 \Omega*m^2 I=-112.6726mA l1=4.43cm b1=4.43cm l2=4.43cm b2=4.43cm$ distance b/w cer

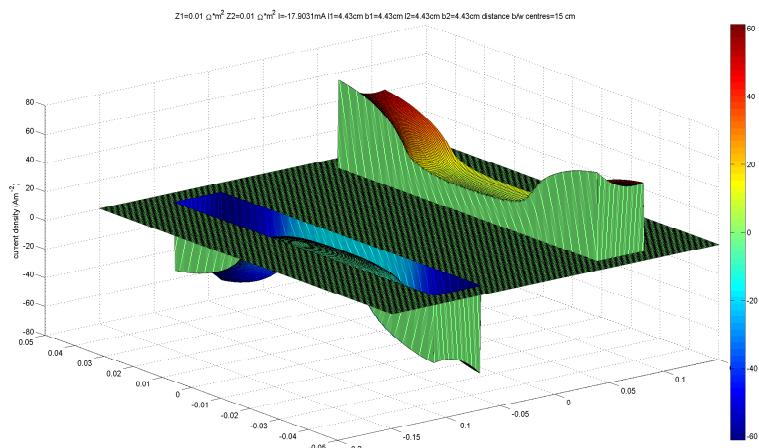
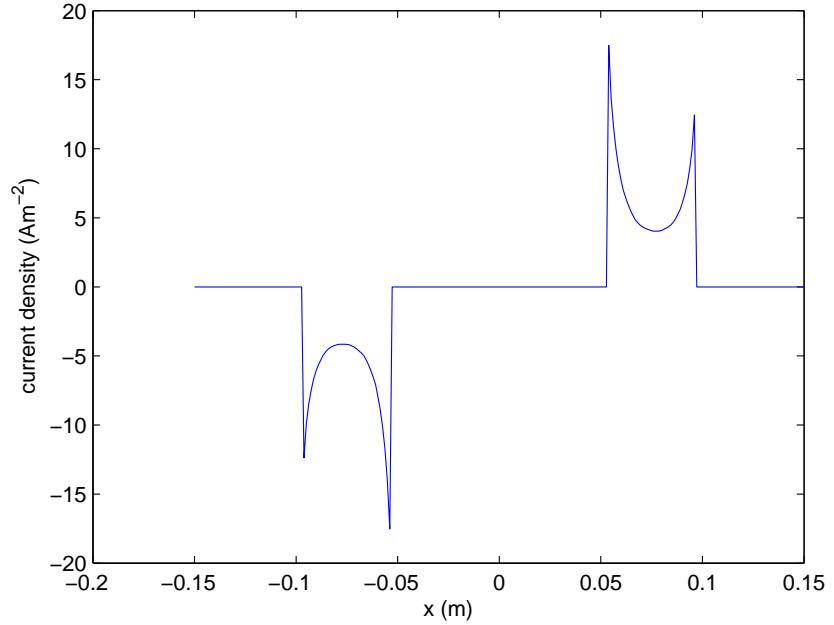


2.3.2 $Z_1=Z_2=0.01 \Omega m^2$, $I=17.903 \text{ mA}$

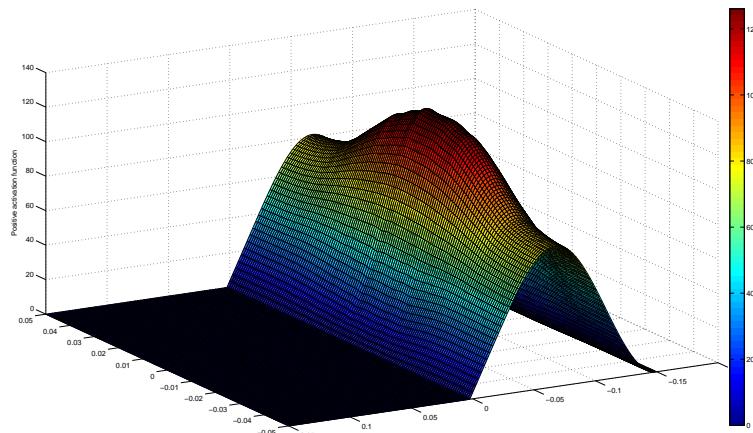
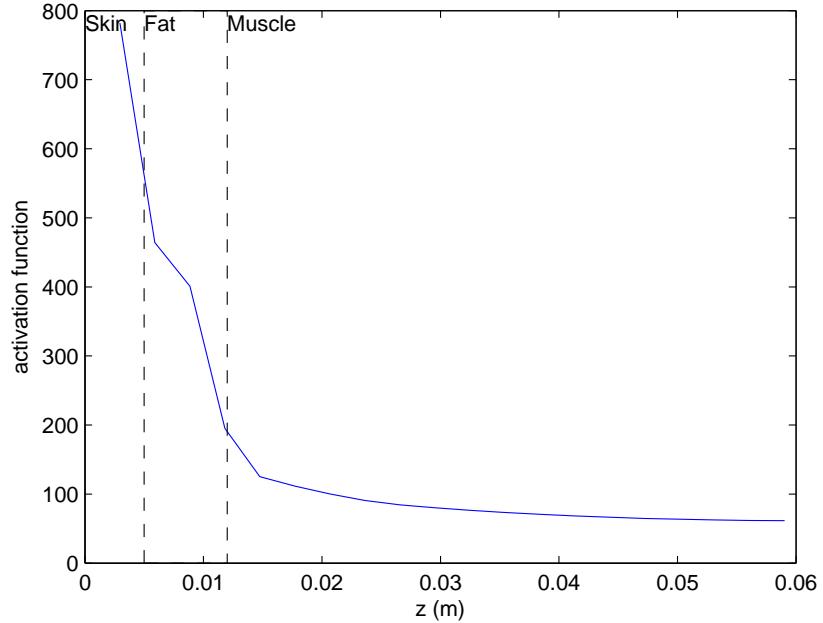
$\lambda^* m^2 Z2=0.01 \Omega^* m^2 I=-17.9031 \text{ mA}$ $I1=4.43 \text{ cm}$ $b1=4.43 \text{ cm}$ $I2=4.43 \text{ cm}$ $b2=4.43 \text{ cm}$ distance b/w centres=15 cm depth=15 mm



$\gamma^* m^2 Z_2 = 0.01 \Omega^* m^2 I = -17.9031 \text{mA} l_1 = 4.43 \text{cm} b_1 = 4.43 \text{cm} l_2 = 4.43 \text{cm} b_2 = 4.43 \text{cm} \text{distance b/w centres} = 15 \text{cm}$



$$\gamma^* m^2 Z_2 = 0.01 \Omega^* m^2 I = -17.9031 \text{ mA} \quad l_1 = 4.43 \text{ cm} \quad b_1 = 4.43 \text{ cm} \quad l_2 = 4.43 \text{ cm} \quad b_2 = 4.43 \text{ cm} \quad \text{distance } b/w \text{ (cm)}$$

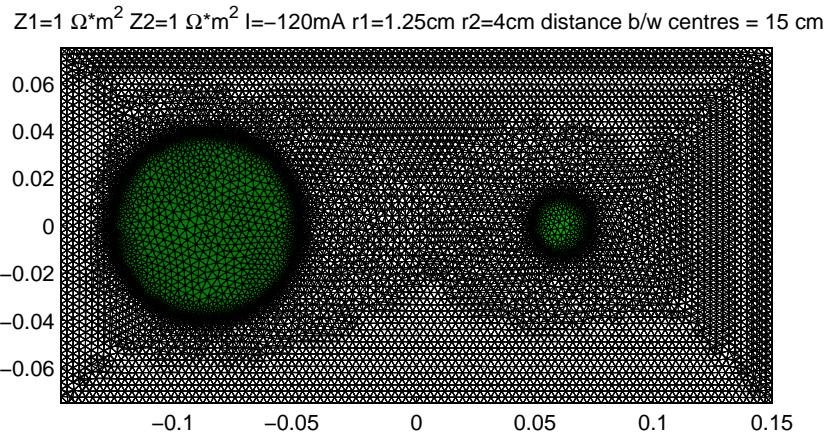


2.3.3 $Z_1 = Z_2 = 100 \Omega \text{m}^2$, $I = 120 \text{ mA}$

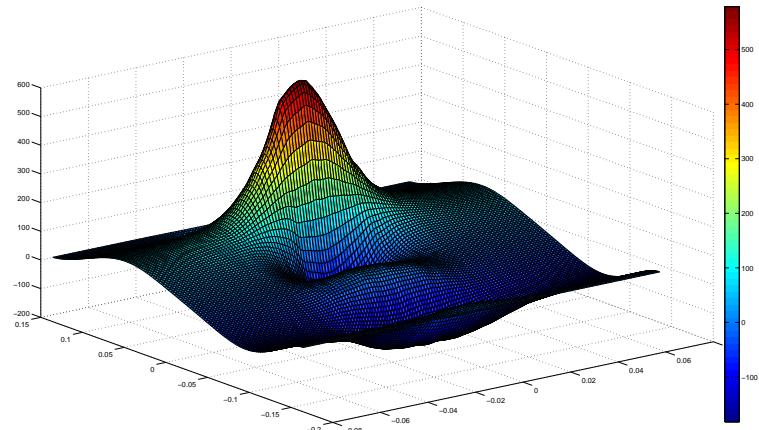
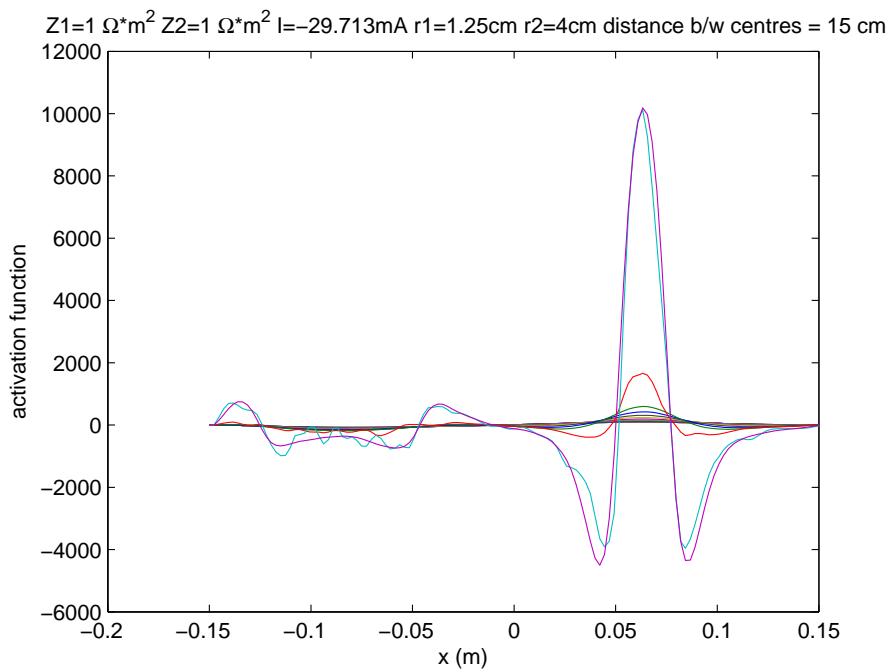
In this case the current density is almost constant and hence this is the same as injecting 120 mA of current.

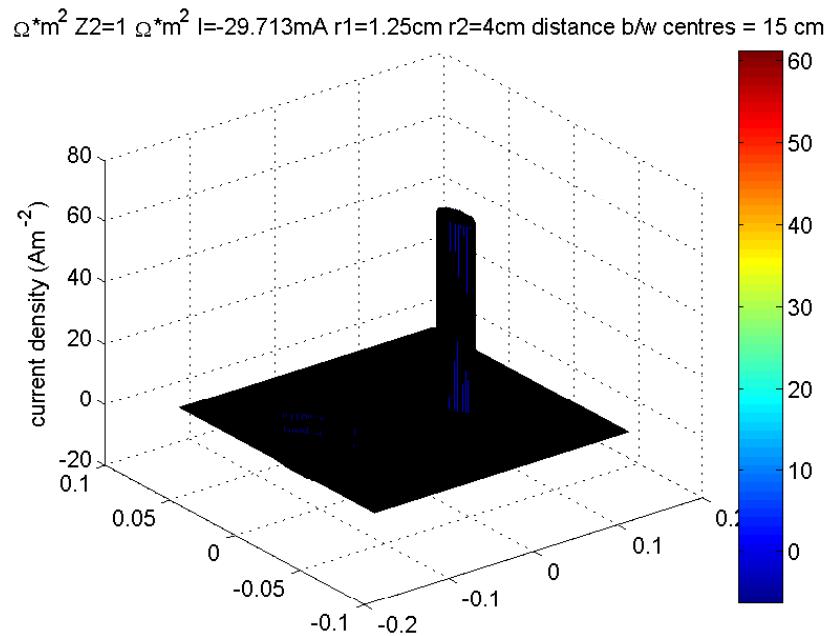
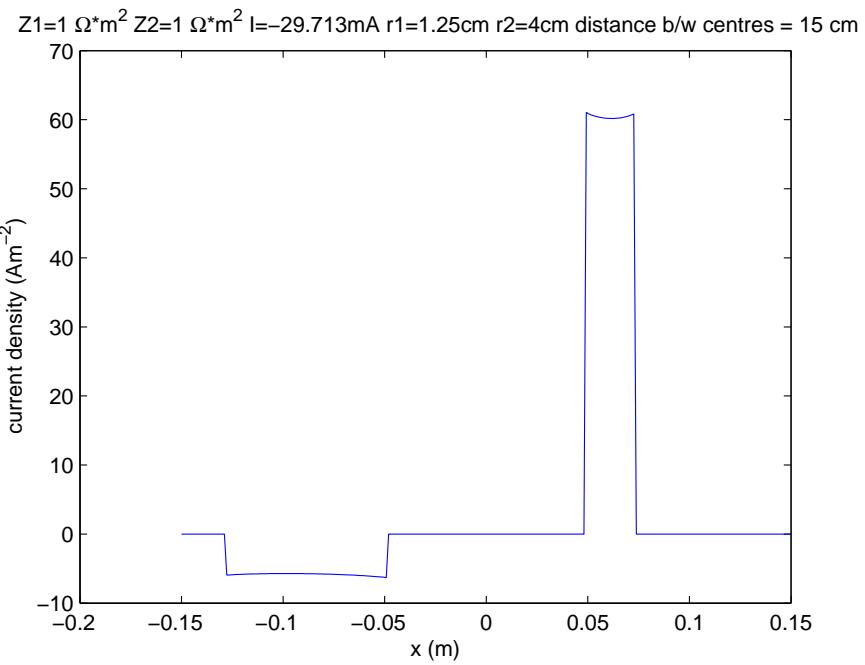
2.4

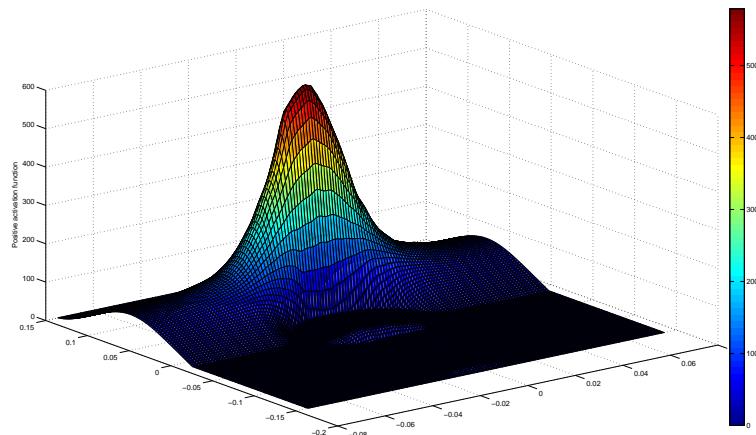
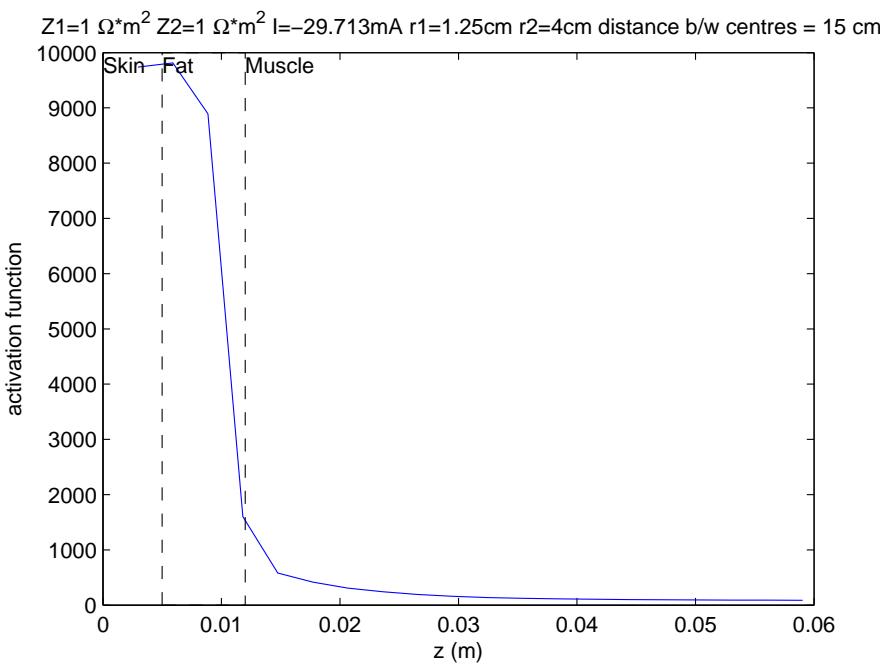
One small circular disk (active) 2.5 cm diameter. Second circular electrode (indifferent) 8cm diameter. Separation 15cm centre to centre.



Parameters - active electrode - $r_1=1.25$ cm, area= 4.9087 cm^2 , indifferent electrode - $r_2=4.0$ cm, area= 50.2655 cm^2 , distance b/w centres= 15 cm, $Z_1=Z_2=1$ $\Omega \cdot m^2$, $I=29.713$ mA

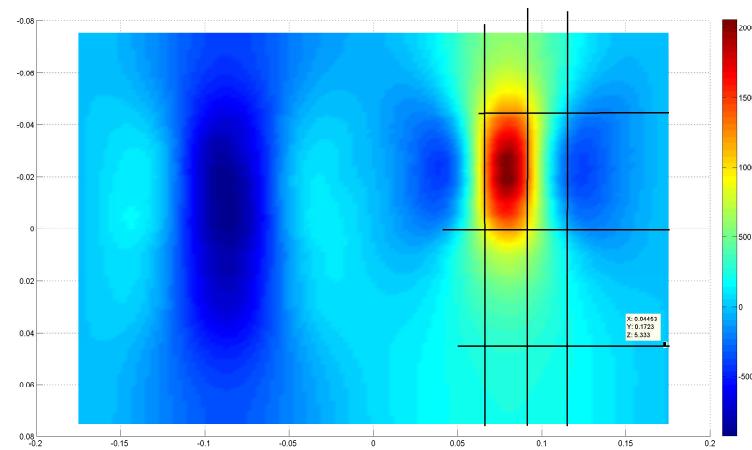
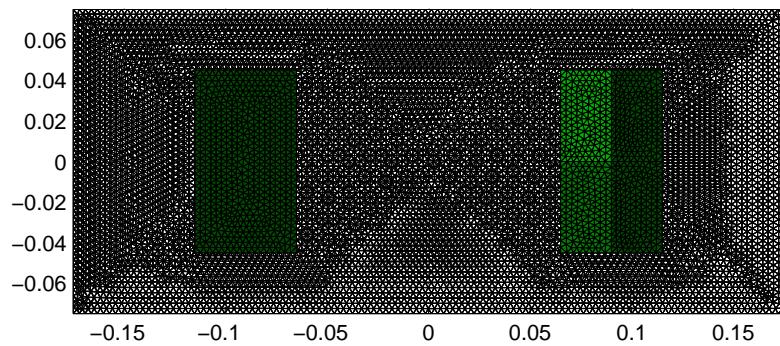


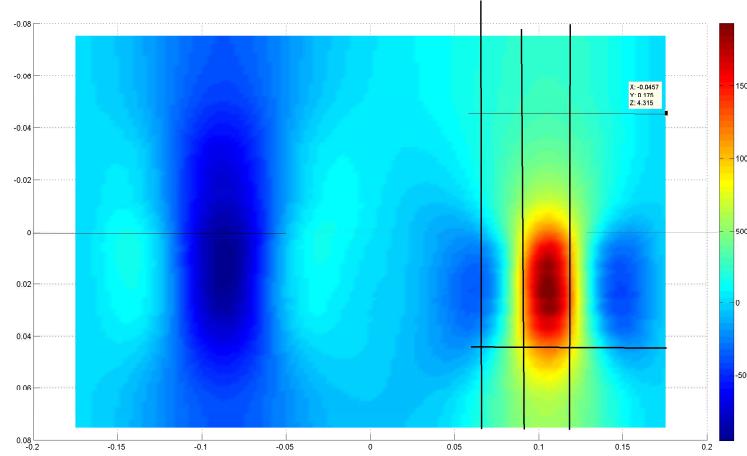




3 Kei's configuration

Some 3d plots of activation function at 15 mm depth using Kei's configuration





4 Summary and Conclusions

Table 2: $I=120 \text{ mA}$, $Z_1=Z_2=1 \Omega\text{m}^2$

S. No.	Configuration	Max current density (Am^{-2})	AF at 12 mm depth (Vm^{-2})	AF at 20 mm depth (Vm^{-2})
1	Side-by-side disks with 15 cm spacing	63.14	1673.2	825
2	Side-by-side disks with 10 cm spacing	63.21	2082.3	993
3	Concentric with outer radius 3.9 cm	62.75	1492.1	810
4	Concentric with outer radius 4.3 cm	62.68	1513.5	857
5	Side-by-side square electrodes	65.09	1599.2	814
6	Side-by-side active and indifferent	246.82	6203.9	1346

The above plots were summarized to compare the configurations. Some conclusions:

- Low values of contact impedance lead to high current density at the edges of the electrodes. Even at the same current levels the activation function is less for low contact impedances. At the same current density, the activation function for low impedance is significantly less. However increasing

Table 3: $I=120$ mA, $Z_1=Z_2=0.01$ Ωm^2

S. No.	Configuration	Max current density (Am^{-2})	AF at 12 mm depth (Vm^{-2})	AF at 20 mm depth (Vm^{-2})
1	Side-by-side disks with 15 cm spacing	171.70	1548.5	750
2	Side-by-side disks with 10 cm spacing	177.57	1521.4	920
3	Concentric with outer radius 3.9 cm	157.87	786.7/1300.9	546
4	Concentric with outer radius 4.3 cm	153.65	841.8/1366.9 ^a	610
5	Side-by-side square electrodes	409.64	1279.3	689

^aIn these cases the maximum magnitude of AF was below the ring electrode

the contact impedance makes no difference to after a point and only increases the applied voltage. Thus in our case the contact impedance of 1 Ωm^2 should be the best choice.

- At medium/high contact impedances all configurations perform almost equally well. The side by side disk configuration with 10 cm distance has the highest magnitude of the activation function. Among the two configurations with concentric electrodes the one with larger outside diameter has lower current density and higher values of activation function in the muscle layer.
- In case of the concentric configuration the peak activation function below the disk and the ring is similar in magnitude. Due to the symmetry, nerves lying anywhere underneath the area covered by the electrodes will get activated. This can help in making the stimulation process tolerant to variations in position or direction of the nerves.
- In case of the side by side active and indifferent electrode configuration, the active electrode has a very small area and so it should be compared keeping the current density fixed. From Table 5, it can be seen that the activation function is comparable to other configurations at 12 mm depth but it drops very fast as the depth increases. Also the area in which the high activation is present is very small and so this configuration requires very precise placement of the electrodes.
- As can be seen from the plots of activation function vs. depth, the activation function falls very rapidly in the fat region (due to its low conductivity). Thus the thickness of the fat region is a limiting factor in increasing the penetration of the activation function.

Table 4: $I=120$ mA, $Z_1=Z_2=100$ Ωm^2

S. No.	Configuration	Max current density (Am^{-2})	AF at 12 mm depth (Vm^{-2})	AF at 20 mm depth (Vm^{-2})
1	Side-by-side disks with 15 cm spacing	61.15	1680.2	827
2	Side-by-side disks with 10 cm spacing	61.15	2101.5	995
3	Concentric with outer radius 3.9 cm	61.13	1514.2	817
4	Concentric with outer radius 4.3 cm	61.13	1534.6	864
5	Side-by-side square electrodes	61.18	1479.0	830

Table 5: $j_{\max}=61.12$ Am^{-2} , $Z_1=Z_2=1$ Ωm^2

S. No.	Configuration	Injected current I (mA)	AF at 12 mm depth (Vm^{-2})	AF at 20 mm depth (Vm^{-2})
1	Side-by-side disks with 15 cm spacing	116.2	1619.5	797
2	Concentric with outer radius 4.3 cm	117.0	1475.6	835
3	Side-by-side square electrodes	112.7	1378.3	706
4	Side-by-side active and indifferent	29.7	1536.1	333

- The square electrodes perform reasonably well for medium/high contact impedances, but at low contact impedance the maximum current density is very high.

Table 6: $j_{\max}=61.12 \text{ Am}^{-2}$, $Z_1=Z_2=0.01 \Omega\text{m}^2$

S. No.	Configuration	Injected current I (mA)	AF at 12 mm depth (Vm ⁻²)	AF at 20 mm depth (Vm ⁻²)
1	Side-by-side disks with 15 cm spacing	42.713	551.2	267
2	Concentric with outer radius 4.3 cm	47.731	334.8/543.7 ^a	243
3	Side-by-side square electrodes	17.903	190.9	103

^aIn this case the maximum magnitude of AF was below the ring electrode