EMC/EMI Issues in Biomedical Research

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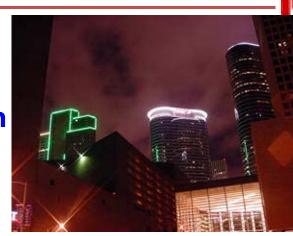
UH: close to downtown of Houston
35,066 students



ECE Department: 35 faculty members, 250 graduate students

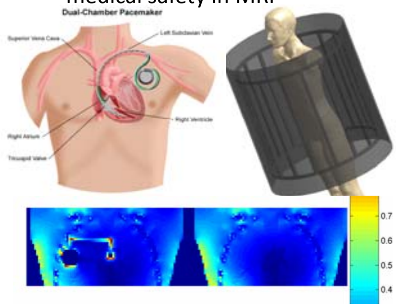
Electromagnetic Research at University of Houston:

NSF Center For Electromagnetic Compatibility Research

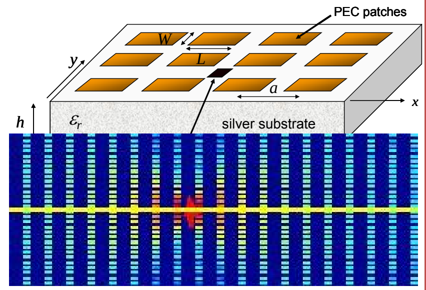
Areas:
Computational Electromagnetics
Antennas
High-Speed Signal Propagation
Bioelectromagnetics
Nano-devices
Wireless Propagation

Faculty Members:
6 faculty members
IEEE Board of Directors
past president of AP society
4 IEEE Fellows

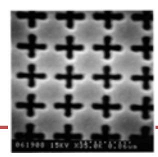
medical safety in MRI

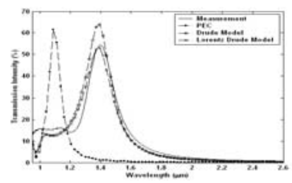


Design of periodic structures



Nano-scale FSS modeling

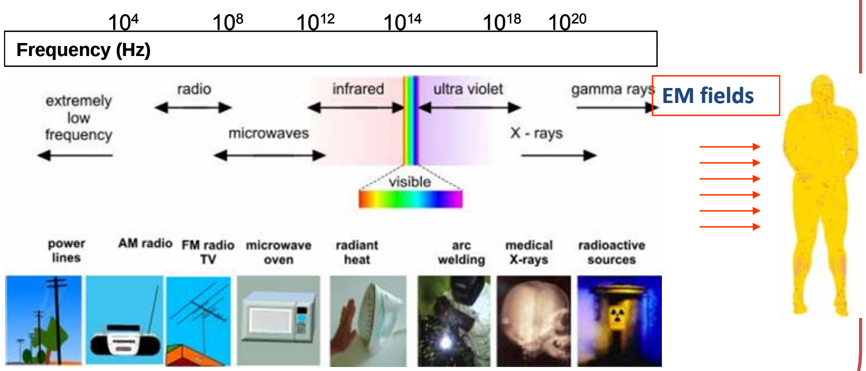




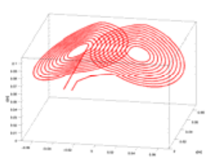
Outline

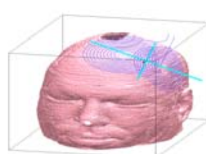
- Introduction
- Human subject models
- Methodologies in modeling
- Applications
  - Pregnant woman exposed to walk-through metal detector
  - Pregnant woman under exposure to magnetic resonance imaging
  - Safety evaluation of metallic implants in magnetic resonance imaging
  - Interactions between medical implants and vehicular mounted antennas
- Summary and future work

Introduction



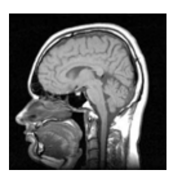
Magnetic stimulation in human head (low frequency)





- severe depression
- auditory hallucinations
- migraine headaches
- tinnitus

Magnetic resonance imaging (radio frequency)



visualize the inside of living organisms

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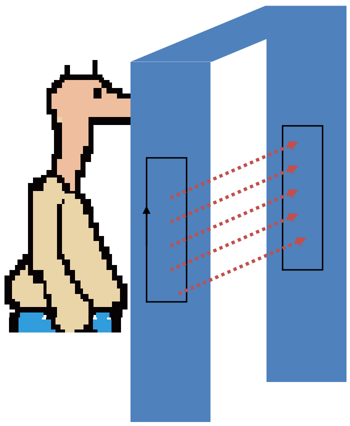


A head-to-toe uniform detection field

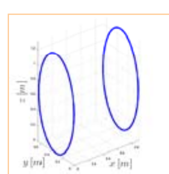
Pinpoint Detection with DSP Chip

- **The problem of human exposure to high/low frequency electromagnetic fields has been the subject of many studies.**
  - **Electromagnetic and temperature analysis of high-frequency exposure**
    - **SAR (energy deposition)**
    - **Temperature (thermal distribution)**

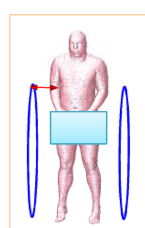
EM fields → Energy deposition → Tissue heating

  - **Calculate induced current density and induced electric field in human body due to extremely-low-frequency exposure**
    - ***J (current density) & E (electric field)***

EM fields → Induced current



Anti theft device model



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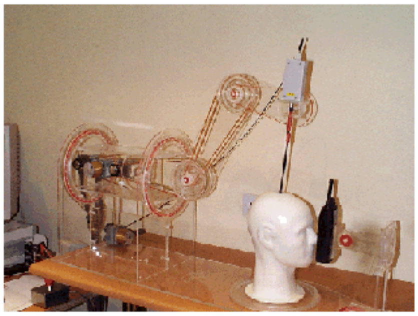
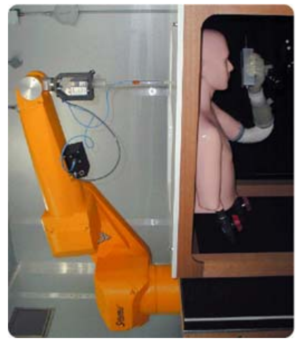
Approach 1: Experimental measurement





disadvantages:

I. difficult to make models.
II. filling material is homogeneous.
III. difficult to make measurement equipments for various EM exposure.

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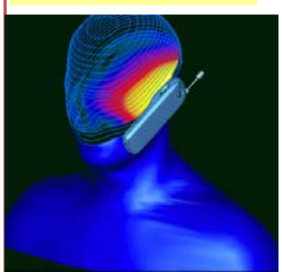
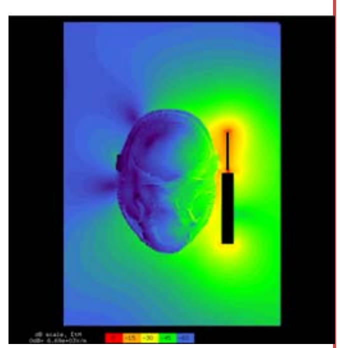
Approach 2: Numerical simulation

CAD model
+ external EM source



Numerical
method



advantages:

I. easy to make CAD models (difficult to make for experiments).
II. able to analyze inhomogeneous models
III. easy to model various external EM fields.

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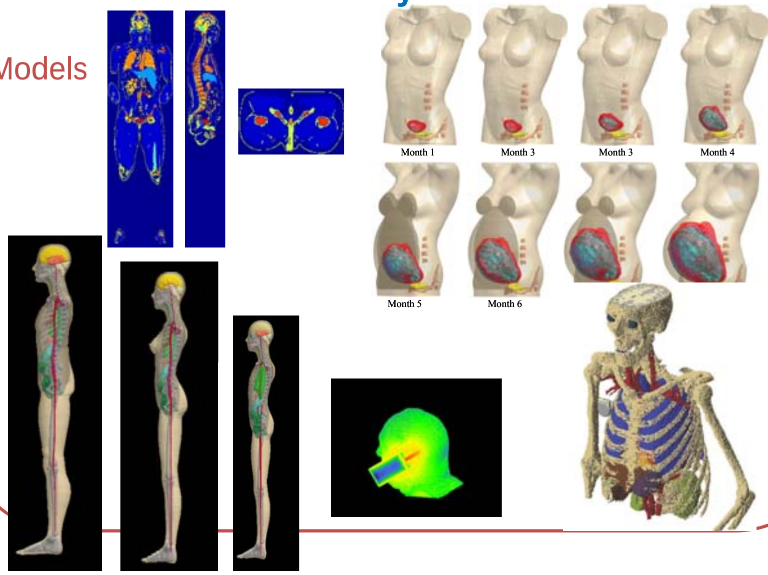
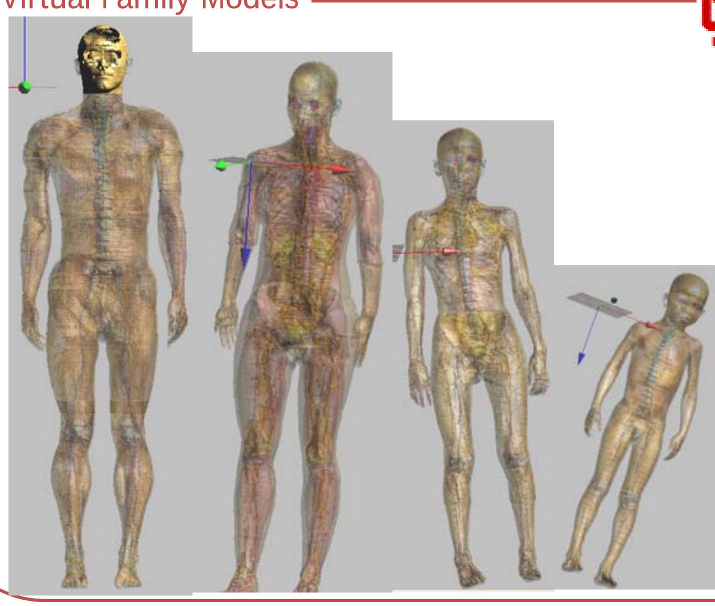
Human Subject Models

Models



Virtual Family Models



Tissue parameters

Dielectric & thermal properties

CAD Model (including different internal organs/tissues)

↓

Assign tissue parameters for each internal organs/tissues

↓

Final model (realistic human body)

↓

Numerical simulation

		64 MHz		128 MHz	
Tissue	ρ[kg/m^3]	σ [S/m]	ε_r	σ [S/m]	ε_r
Body	1006	0.49	52.54	0.51	46.23
Placenta	1058	0.95	86.50	1.00	73.19
Embryonic Fluid	1055	1.50	69.13	1.51	69.06
Bladder	1055	0.29	24.59	0.30	21.86
Bone	1990	0.06	16.69	0.067	14.72
Fetus	987	0.39	42.68	0.412	37.60
Uterus	1052	0.91	92.19	0.961	75.47

	C	K	B_0	A_0
Tissue	[J/kg/°C]	[W/m/°C]	[W/m^3/°C]	[W/m^3]
Body	3270	0.43	2400	537
Placenta	3840	0.50	0	0
Embryonic Fluid	3840	0.50	0	0
Bladder	3300	0.43	9000	1600
Bone	1260	0.40	3300	610
Fetus	3105	0.39	2250	461
Uterus	3430	0.51	6000	1075

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Modeling Techniques

- Low frequency bio-electromagnetic modeling
  - Impedance method ➡ Induced current & electric fields
- High frequency bio-electromagnetic modeling
  - Finite difference time domain (FDTD) method ➡ Specific absorption rate
- Thermal modeling in bio-electromagnetic
  - Finite difference solution of bio-heat equation ➡ Temperature distribution
- Equivalent source ➡ Generate required magnetic fields for impedance method

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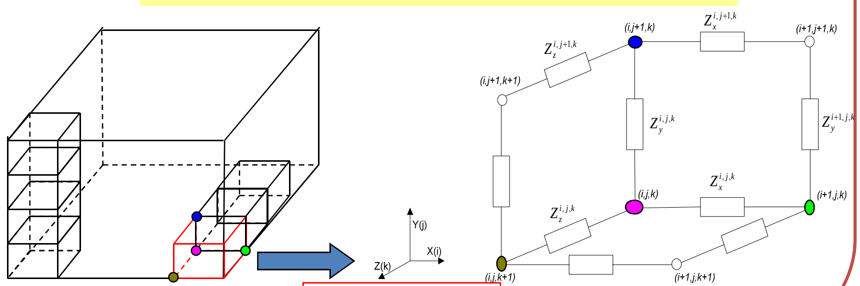
Method1: Impedance method

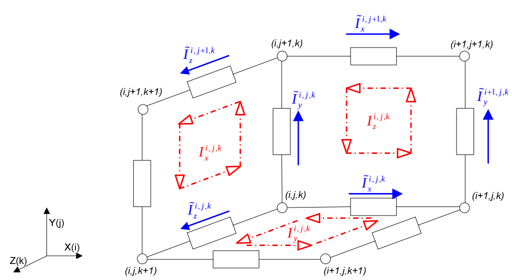
- **Impedance method**
  - **Efficient for ELF calculation**
  - **Easy to implement**

Equivalent circuit network for impedance method



$$Z_x = \frac{\Delta x}{\Delta y \Delta z(\sigma_x + j\omega\varepsilon_x)}$$

Impedance method



Kirchhoff voltage equations

$$\sum \tilde{I}Z + j\omega\mu_0 H\cdot\hat{n} = V$$

$$Z_x^{i,j,k}\tilde{I}_x^{i,j,k} + Z_y^{i+1,j,k}\tilde{I}_y^{i+1,j,k} - Z_x^{i,j+1,k}\tilde{I}_x^{i,j+1,k} - Z_y^{i,j,k}\tilde{I}_y^{i,j,k} = emf_z^{i,j,k}$$

$$emf = -\frac{\partial}{\partial t}\iint \bar{B}\cdot d\bar{s}$$

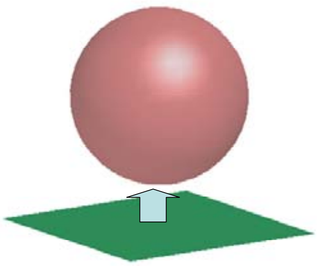
$$\tilde{I}_z^{i,j,k} = I_x^{i,j,k} + I_y^{i+1,j,k} - I_x^{i,j+1,k} - I_y^{i,j,k}$$

$$\sum_{n=1}^{3} a_{mn}^{i,j,k} I_n(i,j,k) = emf_m;\ 1 \le m \le 3$$

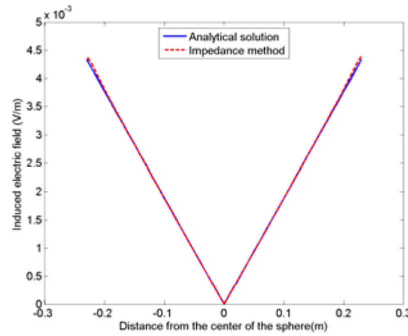
Numerical validation example

radius=0.25m

σ=0.1



B= 1 Tesla
freq=60 Hz



Method 2: FDTD

Modeling of interaction of electromagnetic fields with human bodies at high frequency

SAR (energy deposition)

Efficient numerical technique to solve electro-magnetic wave problems

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu}\nabla \times \vec{E} - \frac{\rho'}{\mu}\vec{H}$$

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon}\nabla \times \vec{H} - \frac{\sigma}{\varepsilon}\vec{E}$$

- Finite Difference Time Domain Method
  - Direct solution method for Maxwell's time dependent curl equations
  - Avoids solving simultaneous equations -- matrix inversion
  - Provides for complexities of structure shape and material composition
  - Very easy to implement compared to FEM/MOM method

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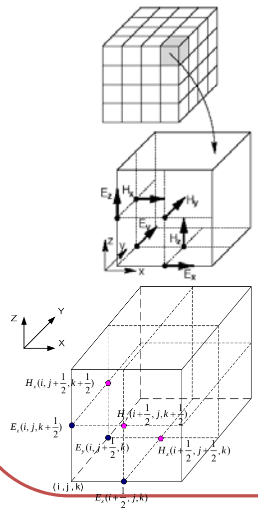
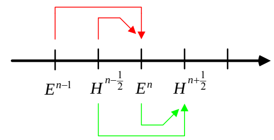
Method2: FDTD

Yee's FDTD Scheme





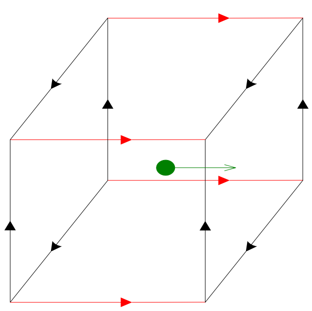
Explicit update scheme

- Easy to implement
- Able to be parallelized

Method2: FDTD

Specific absorption rate (SAR) calculation

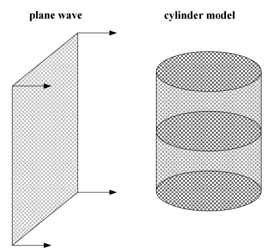
$$SAR = \frac{\sigma |E|^2}{2\rho} = \frac{\sigma(|E_x|^2 + |E_y|^2 + |E_z|^2)}{2\rho}$$

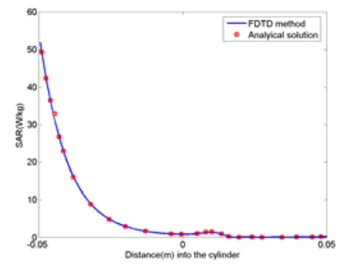


12-field components approach

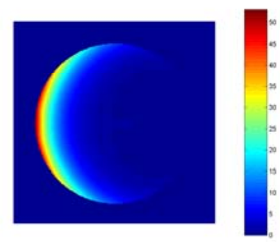
$$E_{x\_center\_i,j,k} = \frac{E_{x\_i,j,k} + E_{x\_i,j+1,k} + E_{x\_i,j,k+1} + E_{x\_i,j+1,k+1}}{4}$$

Method 2: FDTD





Symbol	Physical Property	Value	Units
r	cylinder radius	0.05	m
P	plane wave incident power density	1000	W/m²
f	plane wave frequency	2.45	GHz
ε	relative permittivity	47	-----
σ	conductivity	2.21	S/m
ρ	mass density	1070	Kg/m³
Δx	spatial resolution	0.5	mm



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Method 3: Thermal modeling

- **Thermal modeling/bio-heat equation**

  Temperature-rise computation

  When a human subject in a thermal equilibrium state is exposed to EM fields, the resultant temperature rises may be obtained from thermal modeling (bio-heat equation), which takes into account such heat exchange mechanisms as heat conduction, blood flow, and EM heating.

Bioheat transfer equation (BHTE):

$$C\rho\frac{\partial T}{\partial t} = K\nabla^2 T + A_0 - B(T - T_b) + Q_{EM}$$

$$Q_{EM} = \rho \boxed{SAR} \longleftrightarrow \boxed{\text{from FDTD calculation}}$$

Boundary condition:

$$K\frac{\partial T}{\partial n} = -H_a(T - T_a)$$

Symbol	Physical Property	Units
T	Temperature	$^\circ C$
t	continuous time	s
n	surface normal	–
ρ	mass density	$\left[\frac{kg}{m^3}\right]$
C	specific heat	$\left[\frac{J}{kg^\circ C}\right]$
K	thermal conductivity	$\left[\frac{J}{m\, s^\circ C}\right]$
H_a	convective transfer constant (for environmental ambient temperature)	$\left[\frac{J}{m^2 s^\circ C}\right]$
A_0	basal metabolic rate	$\left[\frac{J}{m^3 s}\right]$
B	blood perfusion constant	$\left[\frac{J}{m^3 s^\circ C}\right]$
m_b	blood mass flow rate	$\left[\frac{m^3}{s\, kg}\right]$
T_b	blood temperature (constant)	$^\circ C$
T_a	environment ambient temperature (constant)	$^\circ C$

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Method 3: Thermal modeling

Modeling procedure

Step		Method
calculation of basal temperature $Q_{EM}=0$	↔	Steady state solution of bio-heat equation
↓		
calculation of SAR ($Q_{EM}=\rho * SAR$)	↔	FDTD method for Maxwell equation
↓		
calculation of new temperature $Q_{EM} \neq 0$	↔	Transient solution of bio-heat equation

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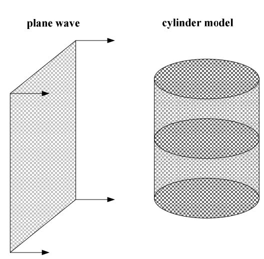
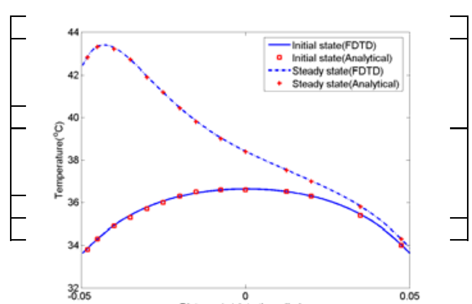
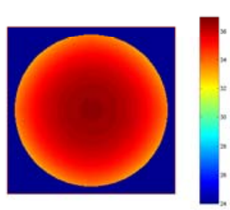
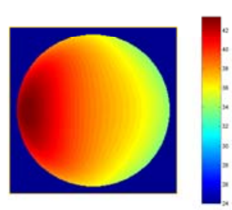
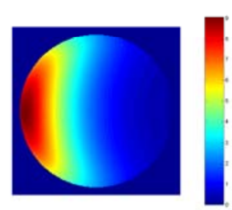
Method 3: Thermal modeling






Basal temperature


Final temperature


Temperature rise

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Method 4: Equivalent source

Types of walk-through metal detector

A head-to-toe uniform detection field

~~coil configurations~~ ~~operation modes~~

Alternative Choice: Measure the magnetic field at a few planes

Method 1. X-ray the walk-through detector

Method 2. Interpolation of the measured field

Method 3. Equivalent source modeling

Pinpoint Detection with DSP Chip

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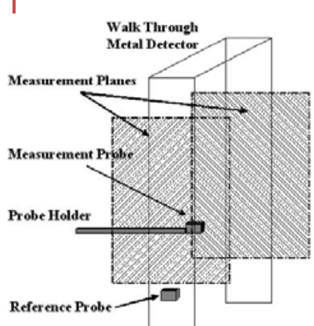
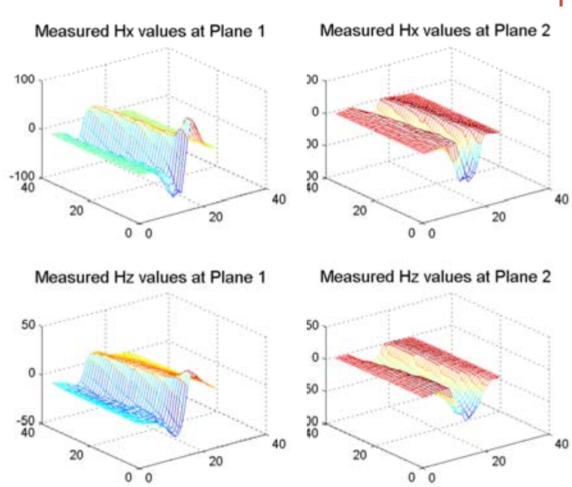
Method 4: Equivalent source

Illustration of magnetic field measurement

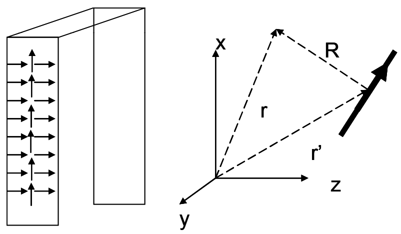


Each plane has a size of 120 *cm* in the horizontal direction and 180 *cm* in the vertical direction.



Method 4: Equivalent source

Equivalent source discretization and the coordinate system



Biot-Savart law

$$\vec{H}=\frac{1}{\mu}\vec{B}=\nabla\times\vec{A}=\int\frac{I(r')d\vec{l}'\times\vec{R}}{4\pi|R|^{3}}$$

$$\begin{bmatrix} H_x \\ \cdots \\ H_y \\ \cdots \\ H_z \end{bmatrix} = \begin{bmatrix} 0 & \cdots & m_{xy} & \cdots & m_{xz} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ m_{yx} & \cdots & 0 & \cdots & m_{yz} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ m_{zx} & \cdots & m_{zy} & \cdots & 0 \end{bmatrix} \begin{bmatrix} J_x \\ \cdots \\ J_y \\ \cdots \\ J_z \end{bmatrix}$$

Equivalent current distribution

Measured data

This equivalent may not be the exact coil configurations but it can produce the same magnetic fields as that of the real coil configuration

least square method

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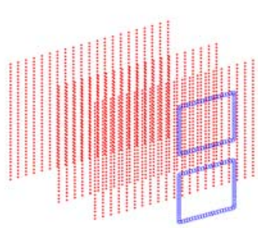
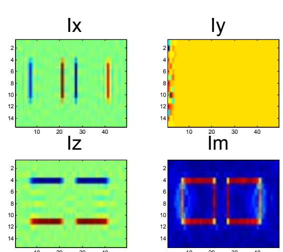
Method 4: Equivalent source

A numerical validation experiment
(magnetic fields generated by the two loop coils)

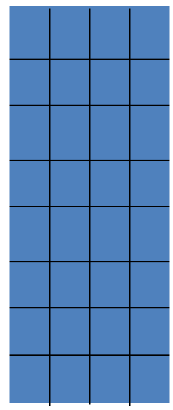




Method 4: Equivalent source

Equivalent source plane

1. **Size**
2. **Mesh density**



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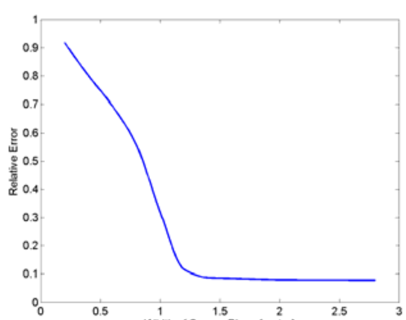
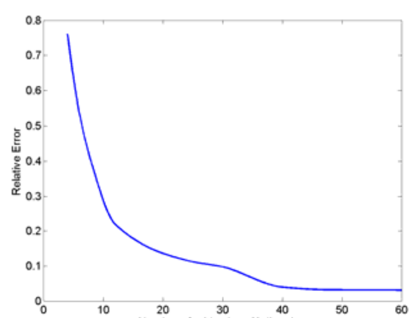
Method 4: Equivalent source

Convergence analysis

$$relative\,error = \frac{\sum \left| H_{simulated} - H_{measured} \right|}{\sum \left| H_{measured} \right|}$$





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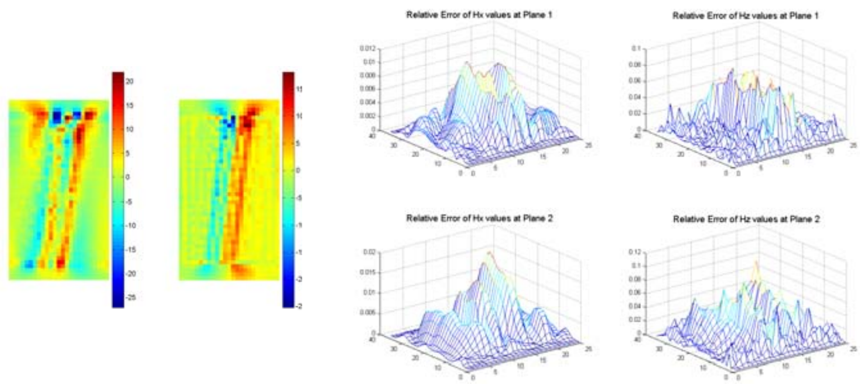
Method 4: Equivalent source



Applications

- Pregnant woman exposed to walk-through metal detector
- Pregnant woman under exposure to magnetic resonance imaging
- Safety evaluation of metallic implants in magnetic resonance imaging
- Interactions between medical implants and vehicular mounted antennas

Application 2: Safety assessment for WTMD

Safety evaluation of walk-through metal detectors

- Walk-through metal detectors are an important part of airport security systems
- Metal detectors use the electromagnetic signal variations as a means to detect metal objects
- Standard was developed based on male models, no safety assessment was performed for pregnant women
- Induced current strength should be used for emission safety assessment (hard to directly measure the induced current strength within human subjects)

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Application 2: Safety assessment for WTMD

Develop a procedure that can be used towards accurate safety assessments for walk through metal detector electromagnetic emission

Measurement of magnetic fields

↓

Equivalent source

↓

Evaluate induced currents (impedance method)

Represent the original walk-through metal detector electromagnetic emission

Able to calculate the magnetic field distribution at any points within the human subjects

Extreme low frequency modeling

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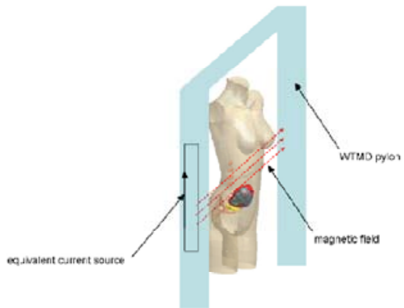
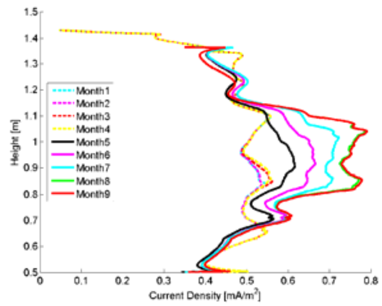
Application 2: Safety assessment for WTMD





	Current density (mA/m²)
ICNIRP Limit	2.0

Application 2: Safety assessment for WTMD

J: induced current density (mA/m²)
E: Induced electric field (mV/m)

		Month1		Month2		Month3		Month4		Month5		Month6		Month7		Month8		Month9	
		J	E	J	E	J	E	J	E	J	E	J	E	J	E	J	E	J	E
bladder	Tissue-averaged	0.18	0.88	0.17	0.82	0.17	0.84	0.17	0.83	0.45	2.15	0.5	2.41	0.54	2.59	0.55	2.63	0.56	2.69
	Maximum (1cm2)	0.23	1.13	0.21	0.99	0.21	1.02	0.21	1.01	0.46	2.21	0.49	2.35	0.51	2.44	0.49	2.37	0.51	2.44
body	Tissue-averaged	0.51	2.24	0.51	2.24	0.52	2.24	0.52	2.25	0.53	2.31	0.56	2.44	0.58	2.53	0.58	2.54	0.58	2.54
	Maximum (1cm2)	1.22	5.29	1.22	5.29	1.22	5.29	1.22	5.29	1.23	5.34	1.61	7.01	1.79	7.78	2	8.7	1.98	8.59
bone	Tissue-averaged	0.12	5.76	0.11	5.56	0.12	5.77	0.11	5.65	0.2	9.79	0.21	10.36	0.22	11.08	0.23	11.37	0.23	11.51
	Maximum (1cm2)	0.54	27	0.53	26.26	0.53	26.27	0.54	26.89	0.6	29.58	0.65	32.42	0.69	34.17	0.67	33.3	0.69	34.01
fetus	Tissue-averaged	0.34	1.84	0.31	1.68	0.35	1.9	0.32	1.73	0.29	1.57	0.33	1.79	0.36	1.93	0.38	2.03	0.38	2.02
	Maximum (1cm2)	0.31	1.65	0.64	3.42	1.14	6.1	1.16	6.22	1.9	10.23	**2.35**	12.65	**2.79**	15.01	**3.09**	16.61	**3.06**	16.45
liquid	Tissue-averaged	0.87	0.58	0.9	0.6	1.08	0.72	1.27	0.84	1.44	0.96	1.63	1.09	1.83	1.22	2.05	1.37	2.05	1.37
	Maximum (1cm2)	0.83	0.55	0.91	0.61	1.35	0.9	1.57	1.04	**2.2**	1.47	**2.86**	1.91	**3.34**	2.23	**3.64**	2.42	**3.69**	2.46
placenta	Tissue-averaged	0.41	0.59	0.48	0.69	0.56	0.8	0.65	0.92	0.62	0.89	0.69	0.98	0.77	1.1	0.85	1.22	0.85	1.22
	Maximum (1cm2)	0.65	0.92	0.68	0.97	0.95	1.35	1.1	1.58	1.45	2.07	1.96	2.79	**2.67**	3.81	**3.08**	4.4	**3.12**	4.46
uterus	Tissue-averaged	0.54	1.1	0.54	1.09	0.64	1.3	0.64	1.31	0.72	1.47	0.84	1.72	0.99	2.03	1.12	2.28	1.12	2.28
	Maximum (1cm2)	0.68	1.38	0.74	1.52	1.12	2.28	1.44	2.94	1.78	3.63	**2.01**	4.11	**2.18**	4.44	**2.39**	4.87	**2.35**	4.79

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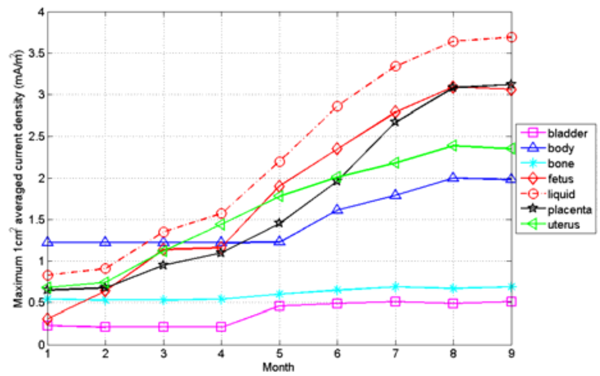
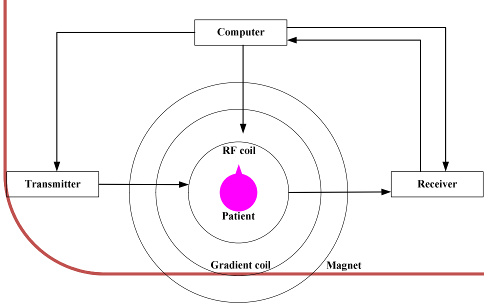
Maximum 1 cm^2 area-averaged current densities for fetus and surrounding tissues (liquid, placenta and uterus) could exceed the ICNIRP safety limit of

2 mA/m^2 beginning with the sixth month of pregnancy.



Application 3: Pregnant women exposed to MRI



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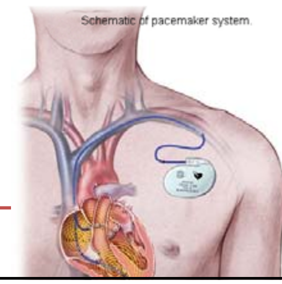
Application 3: Pregnant women exposed to MRI

Second Degree Skin Burn



Application 3: Pregnant women exposed to MRI

Methodology

Develop simulation models including human body and MRI RF coil

Calculate EM fields inside exposed human subjects ⟷ Solve Maxwell's equation by means of finite-difference time domain method

$$SAR = \frac{\sigma}{2\rho}|E|^2$$

Compute temperature rises of tissues ⟷ Solve Bio-heat equation:

$$C\rho\frac{\partial T}{\partial t} = K\nabla^2 T + A_0 - B(T - T_b) + \rho\boxed{SAR}$$

Normalize the simulated data and compare them with the IEC safety limit. ⟷

MRI Operating mode	Whole body SAR (W/kg)	Local SAR_{10g} - Body (W/kg)	Maximum temperature (°C)
Normal	2	10	39.0
First level controlled	4	10	39.0

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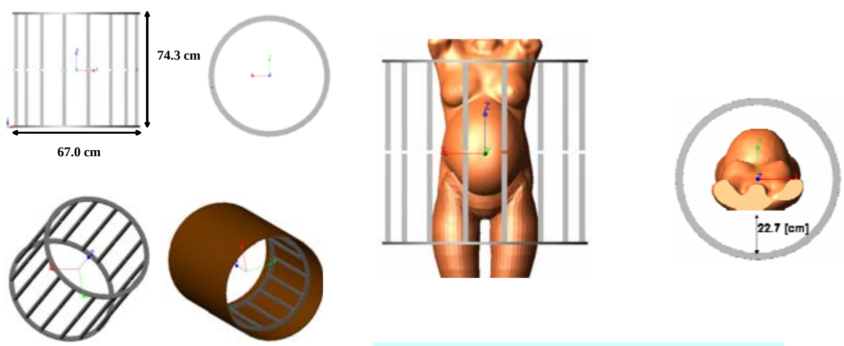
Application 3: Pregnant women exposed to MRI

MRI RF birdcage coil model



64 & 128 MHz
Normal & first level controlled modes

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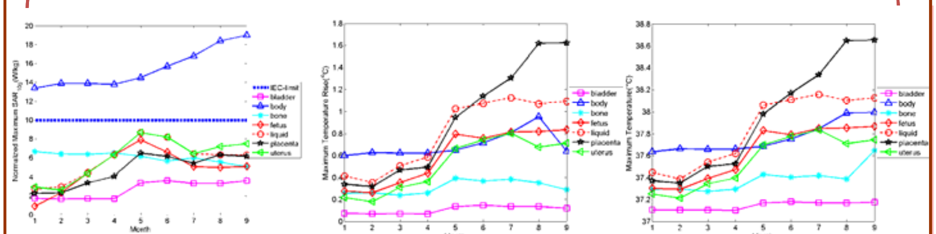
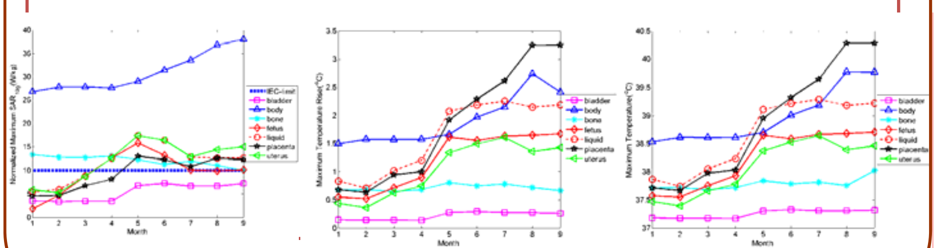
Application 3: SAR and thermal results (64MHz)

Normal mode

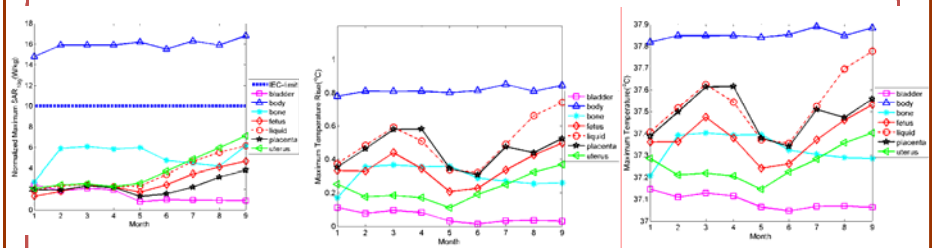


First level controlled mode

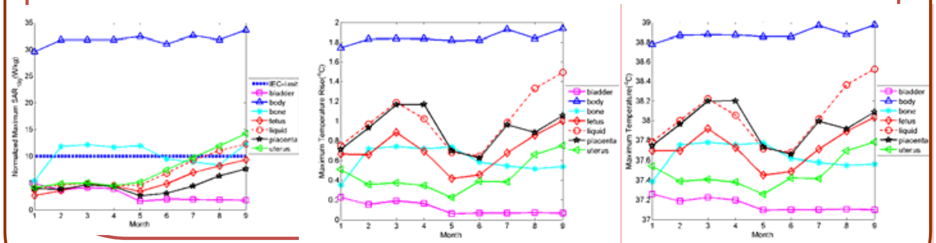


Application 3: SAR and thermal results (128MHz)

Normal mode



First level controlled mode



Fetus		64 MHz		128 MHz	
		Normal Mode	First level controlled mode	Normal Mode	First level controlled mode
Month 1-4	SAR limit	Not exceed	Not exceed	Not exceed	Not exceed
	Temperature limit	Not exceed	Not exceed	Not exceed	Not exceed
Month 5-9	SAR limit	Not exceed	Exceed	Not exceed	Not exceed
	Temperature limit	Not exceed	Not exceed	Not exceed	Not exceed

- Based on the results of this study, we recommend not performing MRI procedures on pregnant women using the first level controlled mode. These results can also be used towards developing safety standards for pregnant woman undergoing an MRI.

- SAR and temperature rise distributions are quite different at the two MRI operating frequencies. Such variation is caused by the different electric field distributions generated by MRI coils at these two frequencies and it is also related to the difference in dielectric parameters at these two frequencies.

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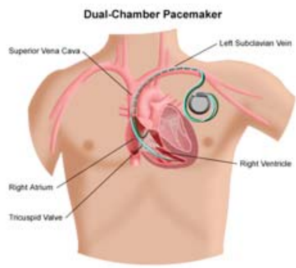
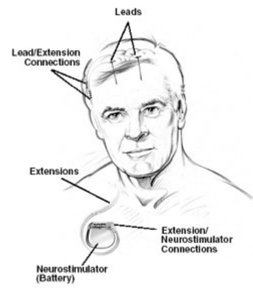
Application 4: Safety of metallic implant within MRI coil





On May 10, 2005, in response to several reports of serious injuries from medical facilities around the country, the FDA issued a Public Health Notification reminding all medical personnel of the importance of properly screening patients for implanted neurological stimulators before administering an MRI

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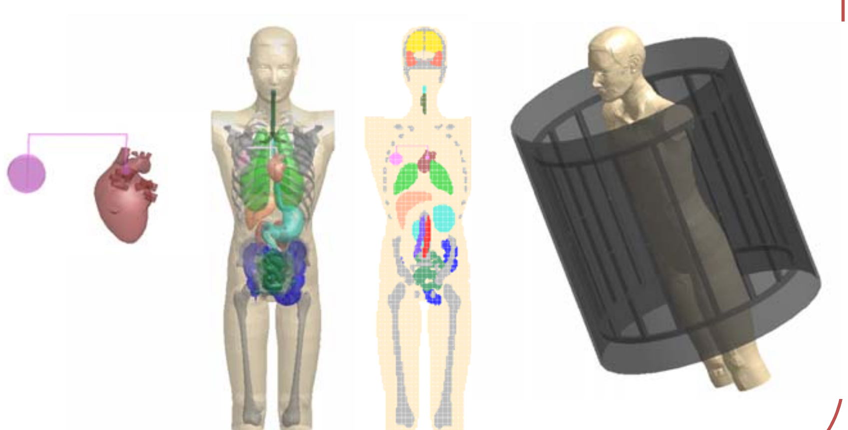
Application 4: Safety of metallic implant within MRI coil

Simulation model



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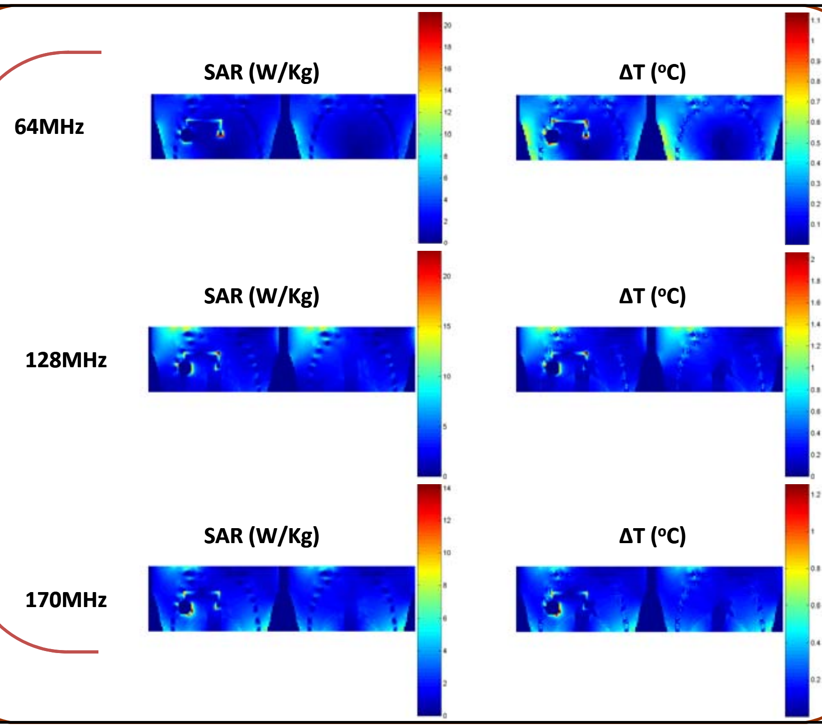

	Maximum SAR (W/kg)						Maximum temperature rise (oC)						Maximum temperature (oC)					
	64MHz		128MHz		170MHz		64MHz		128MHz		170MHz		64MHz		128MHz		170MHz	
	With	W/o	With	W/o	With	W/o	With	W/o	With	W/o	With	W/o	With	W/o	With	W/o	With	W/o
blood	6.47	6.39	14.86	15.07	9.01	8.7	0.91	0.9	1.72	1.69	1	0.98	37.91	37.9	38.72	38.69	38	37.98
bone	2.4	2.37	2.9	2.93	3.25	3.25	2.49	2.48	2.69	2.75	2.1	2.11	39.67	39.66	39.88	39.94	39.29	39.29
brain	0.19	0.18	5.08	5.1	4.51	4.55	0.02	0.02	0.55	0.55	0.46	0.46	37.31	37.31	37.85	37.84	37.75	37.76
eye	0.05	0.04	1.01	1.01	2.51	2.52	0.01	0.01	0.13	0.13	0.33	0.33	37.01	37.01	37.13	37.13	37.33	37.33
heart	**6.49**	**0.95**	**4.44**	**3.25**	**3.21**	**2.41**	**1**	**0.05**	**0.66**	**0.19**	**0.48**	**0.13**	**38.29**	**37.35**	**37.96**	**37.48**	**37.78**	**37.42**
intestine large	19.83	22.02	11.88	11.92	9.33	9.35	2.06	2.04	1.15	1.14	1.03	1.03	37.5	37.5	37.45	37.45	37.64	37.64
intestine small	10.97	10.86	9.44	9.48	10.11	10.13	1.71	1.7	1.18	1.17	0.97	0.96	37.61	37.62	37.4	37.4	37.79	37.79
kidney	3.11	3.08	2.54	2.57	5.48	5.52	0.21	0.21	0.15	0.15	0.34	0.35	38.95	38.94	38.28	38.27	38.32	38.32
liver	5.55	5.6	1.71	1.74	7.9	7.95	0.32	0.32	0.1	0.1	0.49	0.5	38.44	38.49	**38.72**	**38.22**	38.76	38.76
lung	8.44	8.77	7.38	7.51	11.31	11.43	1.15	1.19	**1.42**	**0.92**	1.47	1.47	39.41	39.4	**39.41**	**38.95**	38.7	38.7
muscle	24.53	24.25	19.02	19.16	15.98	16.08	2.88	2.86	**2.16**	**1.87**	1.74	1.74	39	38.99	38.47	38.47	38.26	38.26
Stomach	4.52	4.55	10.5	10.61	12.96	12.98	0.6	0.62	1.2	1.16	1.49	1.49	37.89	37.9	38.49	38.44	38.77	38.77
windpipe	3.27	3.46	6.94	6.98	2.86	2.84	0.49	0.51	1	0.98	0.4	0.38	37.6	37.62	38.11	38.09	37.51	37.49

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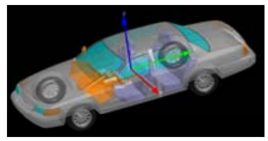
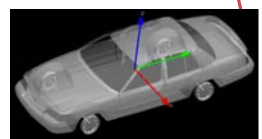
A typical police car (Ford Crown Victoria)



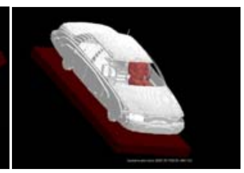
CAD model of the car



Car with medal parts only

According to IEEE P1528.2

Bystander



Passenger

Ground is 30cm thick slab, with relative permittivity 8 and conductance 0.01 S/m, extend 10cm in x and y Direction beyond the car/bystander.

According to IEEE 1528.3 On the Ground Modeling Implementation

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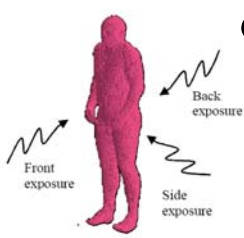
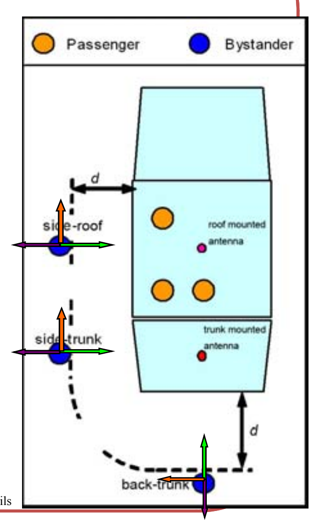
Antenna
1/4 30 MHz
1/4 75 MHz
1/4 150 MHz
1/4 450 MHz
1/4 900 MHz
5/8 150 MHz
5/8 450 MHz
5/8 900 MHz

d-distance
20cm away
100cm away

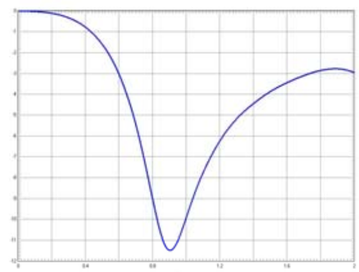


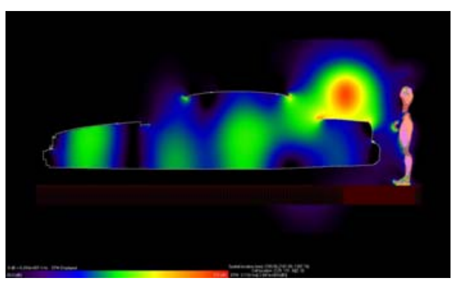
- Three facing direction:
  - Bystander model 1 -->facing the car
  - Bystander model 2 --> facing front
  - Bystander model 3 --> face off the car

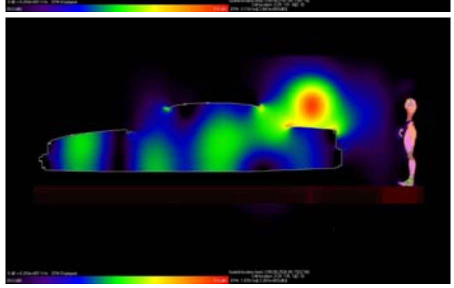
- Four seat modeling:
  - Passenger no additional parts
  - Passenger model 1 --> with medal seat
  - Passenger model 2 --> with spring coils
  - Passenger model 3 --> with both seat & coils



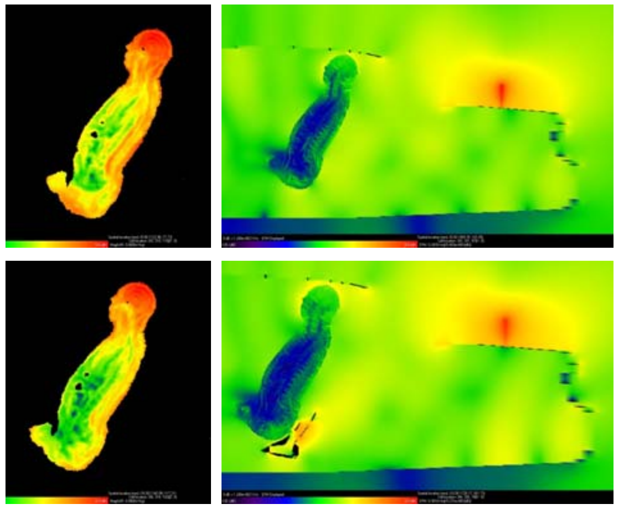
Design of Implantable Antenna





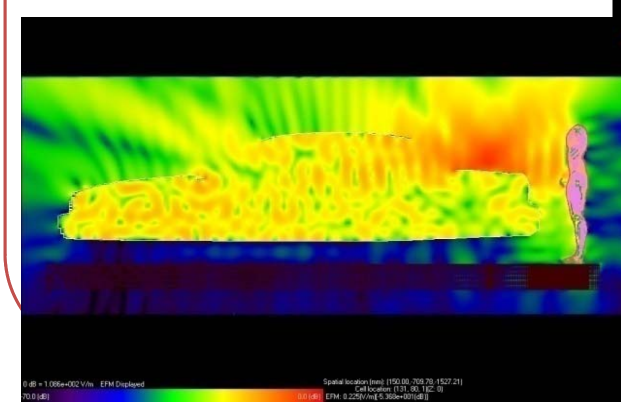


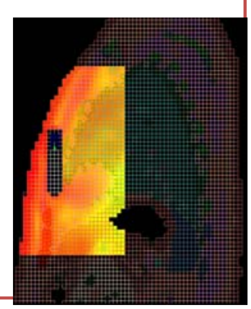
Trunk mounted antenna



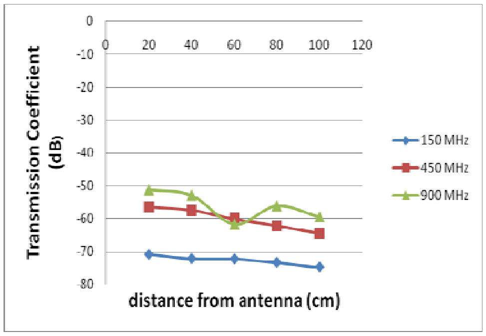
Passenger back center 1/4 antenna at 450MHz

Electric Field Distribution at 900 MHz





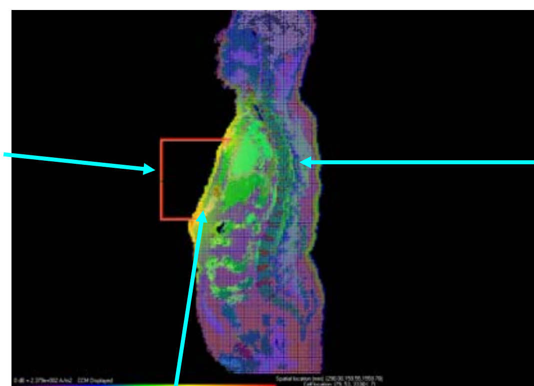
	SAR with Device (W/kg)	SAR W/O Device (W/kg)
150 MHz	0.0028	0.0020
450 MHz	0.0041	0.0034
900 MHz	0.0077	0.0067



Modeling:

Darts at front, induced current within human models

Modeling of taser darts (5 mm into human model)



human model

different color corresponds induced current strength. For example, red color corresponds to large current strength