Numerical Estimation of TASER CEW Current Flow and Effects on Human Body

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Conducted-Energy Weapons: Background

- Conducted-energy weapons (CEW) deliver pulsed currents:
  - That are brief
  - Present high-voltages
  - Carry low-charge electrical pulses
  - Designed to temporarily incapacitate subjects through strong neuromuscular activation.
- TASER devices are most commonly used CEWs
- They are used as non-lethal weapons by law enforcement personnel to subdue suspects, and by civilians for personal defense.
- TASER devices utilize compressed nitrogen to project two small probes up to various ranges of 15, 21, 25 or 35 feet at a speed of over 160 feet per second.

CEW: Background

- Pulse transmitted through trailing wires
- Probes make contact with the body or clothing
- Designed result: immediate loss of the person's neuromuscular control:
  - initial reaction being gravitational dysreflexia (i.e. fall to the ground)
  - loss of ability to perform coordinated action for the duration of the pulse

CEW: Background

- TASER stimuli override the motor nervous system and block the command and control of the human body
- Conventional stun devices stimulate sensory neurons for pain compliance and can be over-ridden by a focused individual
- TASER CEWs directly stimulate pre-endplate motor nerve tissue, causing incapacitation regardless of subject's mental focus, training, size, or drug induced dementia

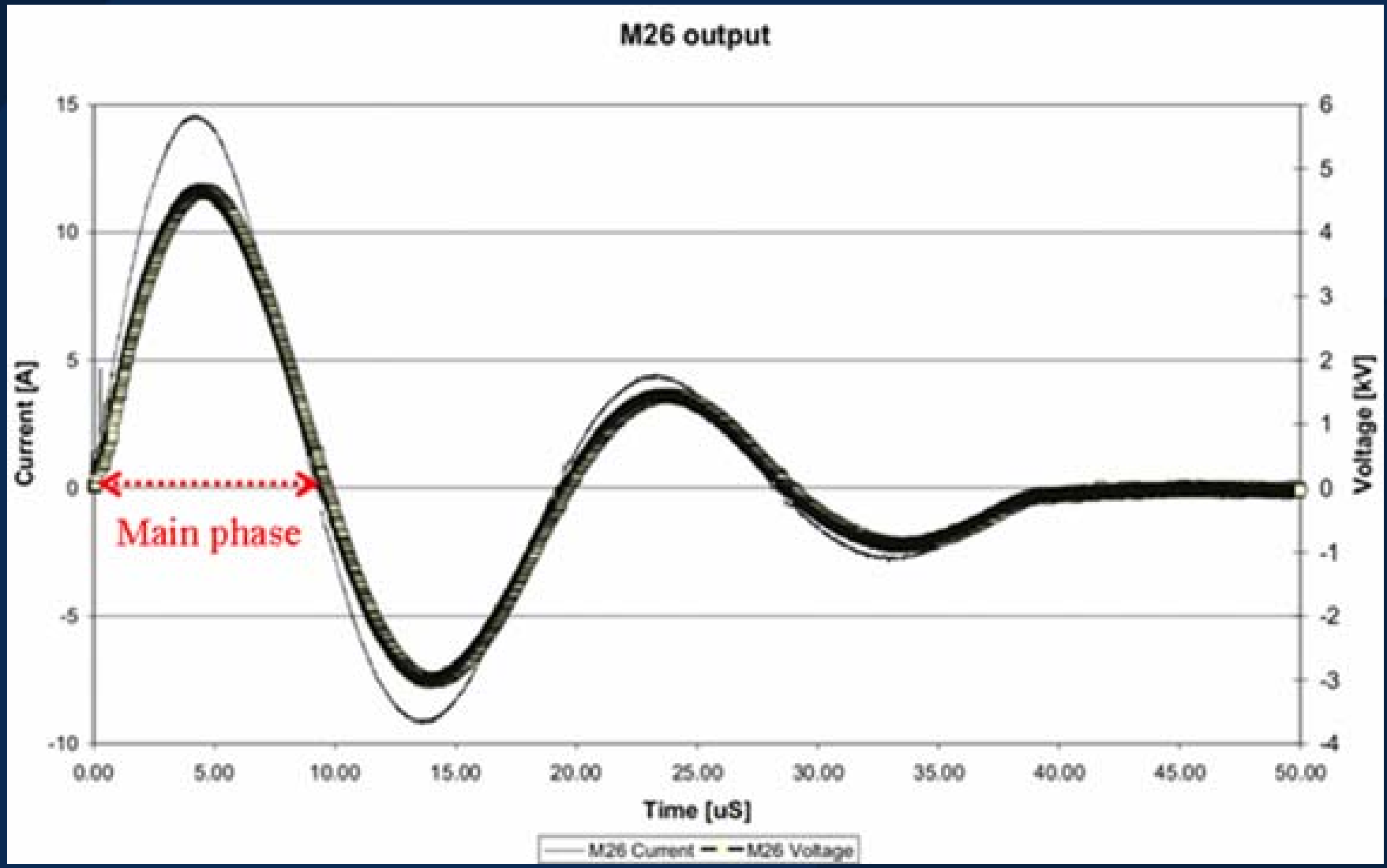
CEW: Background

- The most popular TASER CEW models supplied to law enforcement agencies are:
  - ADVANCED TASER M26
  - TASER X26

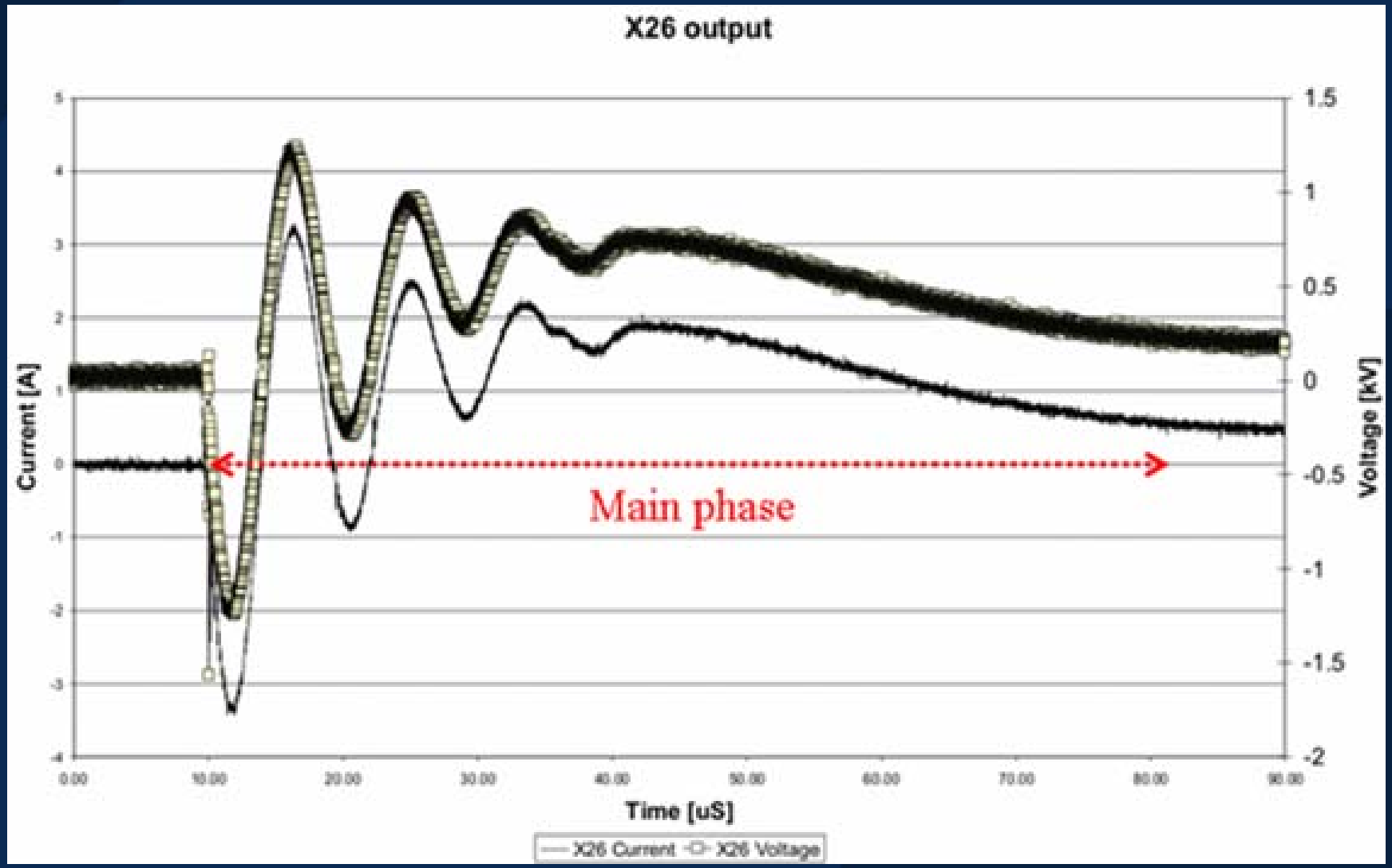
Specifications for M26 and X26 TASER CEWs

Specification	M26	X26
Open-circuit peak voltage [kV]	50	50
Output voltage in typical load [kV]	5	1.2
Pulse duration [μs]	40	100
Total per second discharge (“on”) time [ms]	0.8	1.9
Rated stored energy [J/pulse]	1.76	0.36
Energy delivered in typical load [J/pulse]	0.5	0.07
Nominal internal power rating [W]	26	7
Power delivered in typical load [W]	10	1.3
Charge in the main phase [μC]	85	100
Pulse rate [pulse/s]	20 ± 25%	19
Total delivery duration [s]	5	5
On-demand delivery termination	Yes	Yes
Power source	8 AA NiMH rechargeable or Alkaline cells	Two 3-V Li CR123 cells

Typical waveforms: ADAVANCED TASER M26



Typical waveforms: TASER X26



Finite Element Modeling

- The presentation analyzes current and electric field distributions and effects based on two finite element models (FEM):
  - First model looks at distributions in skeletal muscle and deep body tissues
  - Second model is a whole body model and looks at distributions inside the heart

Methods: *Skeletal muscle activation by pulsed electric fields*

- Motor neurons:
  - chronaxie ~ 140 μs
  - rheobase E field ~ 0.06 to 0.15 V/cm for excitation at axon terminations such as motor end-plates;
- Strength-duration correction of needed E field strength for the M26: (1 + 140/10)x(0.06 to 0.15 V/cm) = 0.9 to 2.25 V/cm
- Strength-duration correction of needed E field strength for the X26: (1 + 140/70)x(0.06 to 0.15 V/cm) = 0.18 to 0.45 V/cm
- Irreversible electroporation E field 1600 V/cm

Methods: *Skeletal muscle activation by pulsed electric fields*

- Based on these values:
  - E field required to successfully activate motor nerves with the M26 and X26 has to exceed 0.18-2.25 V/cm
  - To avoid irreversible electroporation E has to be less than 1600 V/cm

- This yields a worst-case range for the E field strength of 2.25-1600 V/cm, to ensure successful activation with either device while also avoiding electroporation

Methods: 3-D Finite Element Model

Regions

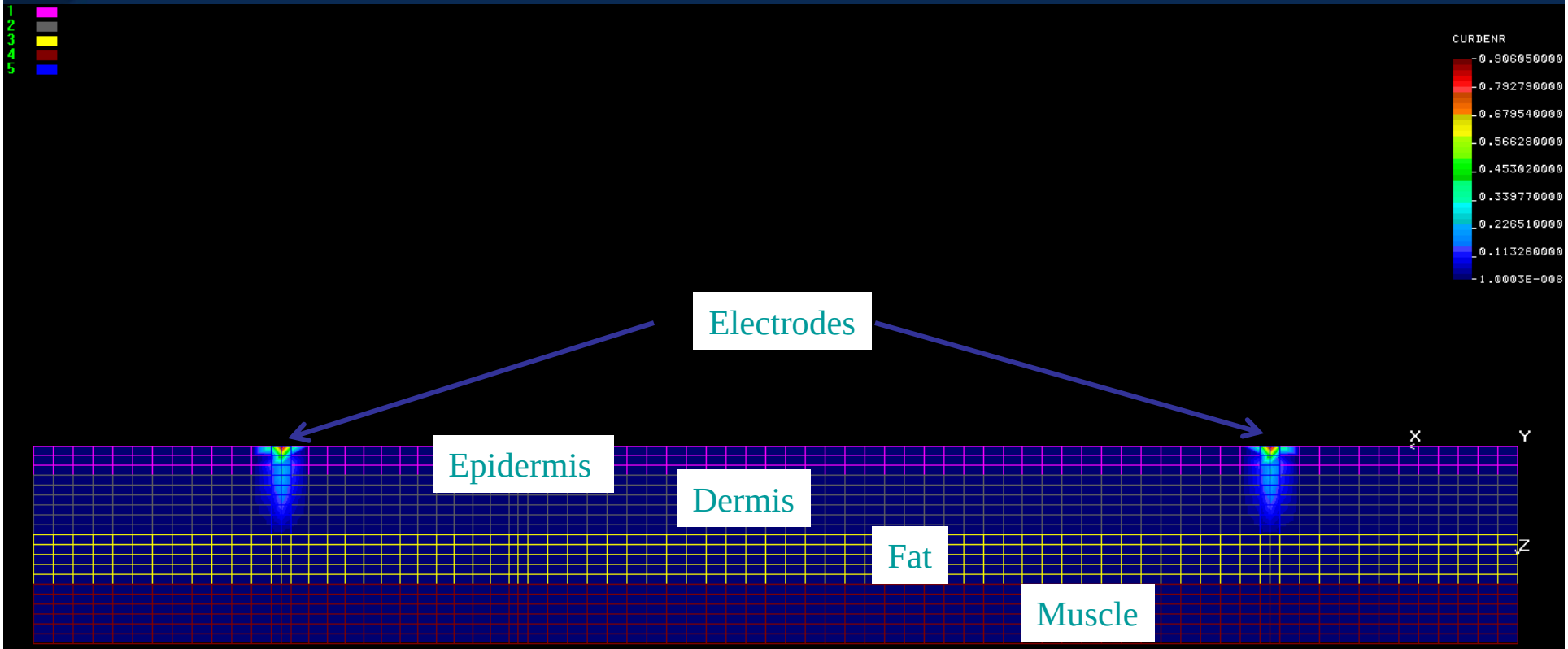
- Epidermis – 3 mm
- Dermis – 6 mm
- Fat – 5 mm (worst case scenario, typical human fat layer thickness is 20-30 mm – see Tchou model)
- Muscle – 6 mm
- Electrodes – 9-mm long, 2-mm diameter (fully penetrated - worst case scenario)

- Nodes: 45360
- Elements: 41080 hexahedral elements
- Model: 15-cm long, 5-cm wide, 2-cm deep
- Electrodes: 10 cm apart
- Voltage boundary conditions: 1000 V
- Steady-state solution

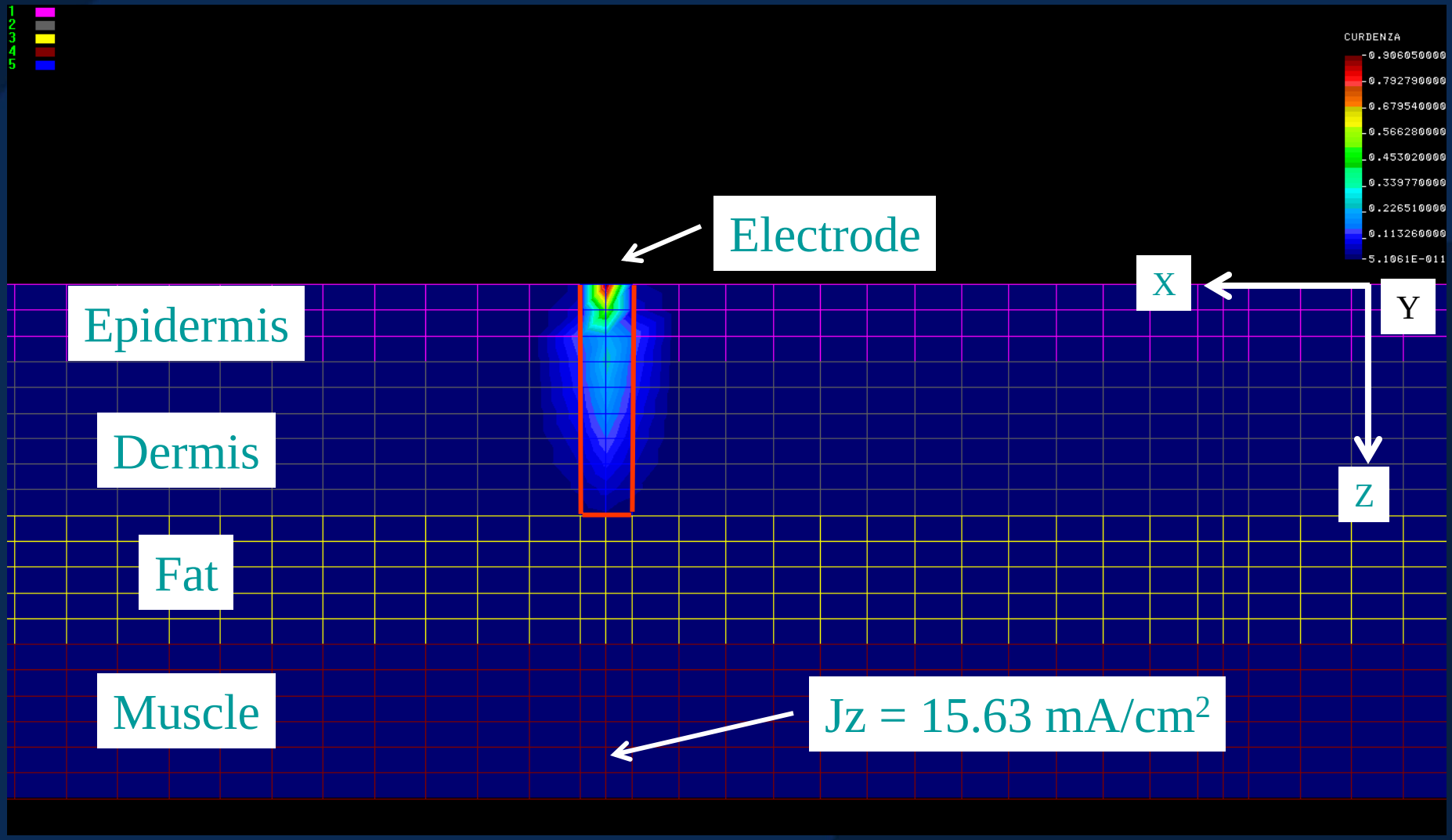
Methods: 3-D Finite Element Model

- Material properties (electrical resistivity)
  - Epidermis – 1 MΩ·cm
  - Dermis – 500 Ω·cm
  - Fat – 2200 Ω·cm
  - Muscle – anisotropic layer
    - $\rho x = \rho y$ = 200 Ω·cm (longitudinal)
    - ρz = 1000 Ω·cm (transversal)
  - Electrodes – 0.001 Ω·cm

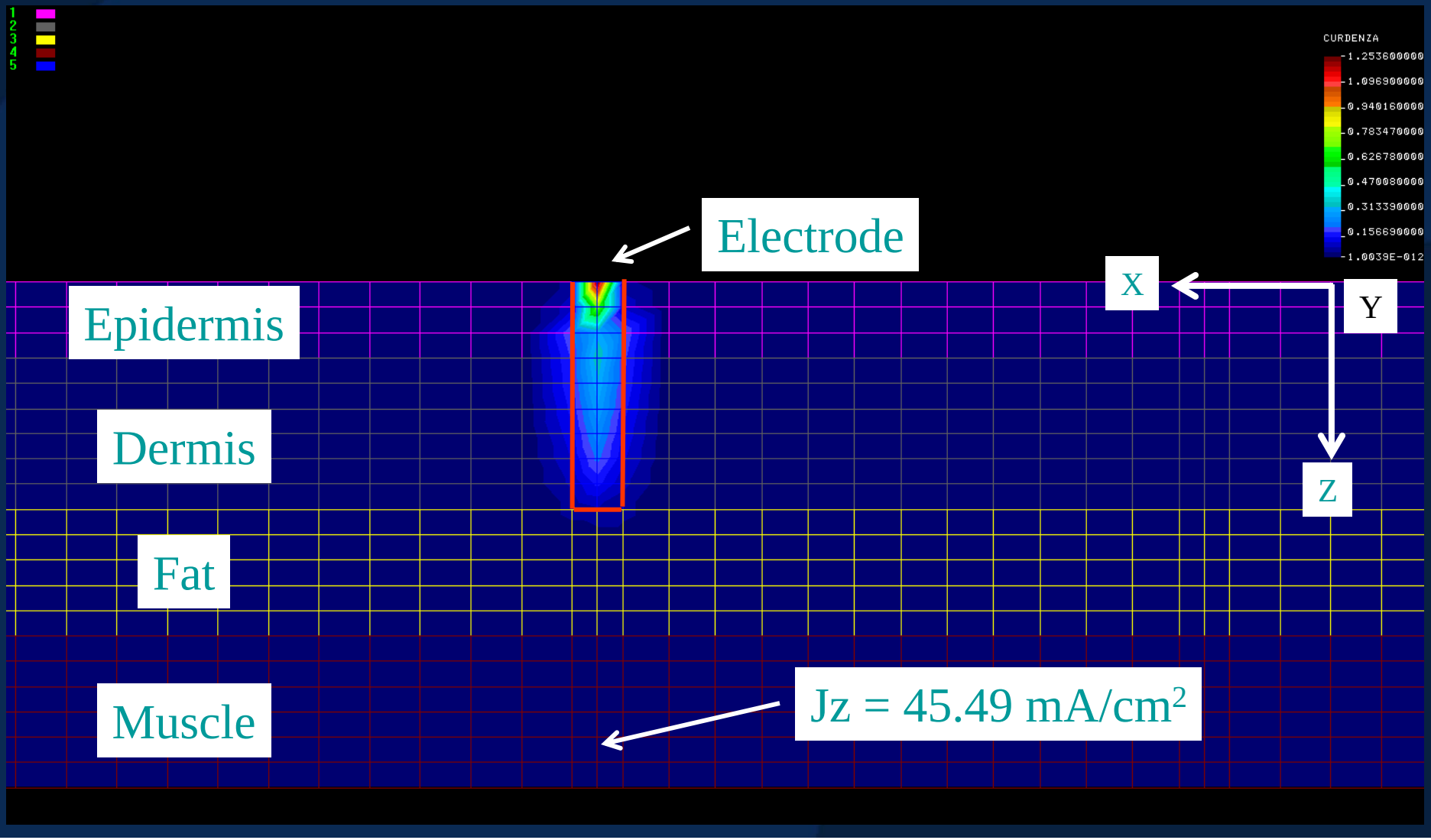
Results – Current density distribution



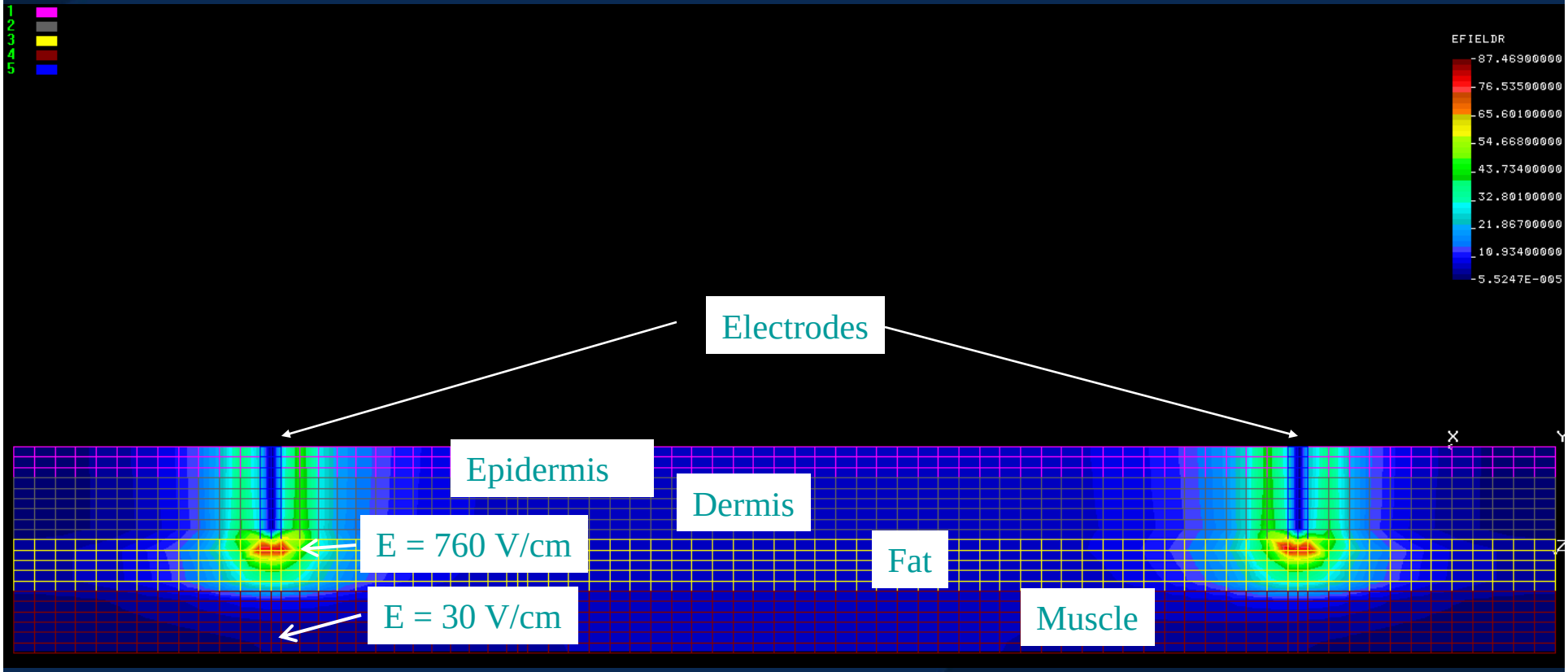
Results – Transverse J distribution



Removal of fat and muscle anisotropy increases J by 200%



Results – Electric field strength distribution



Electrical Shell Effect of Fat and Skeletal Muscle

Condition	J_{trans} [mA/cm^2]	J_{long}/J_{trans}	Comments
Thin body with 5-mm fat and anisotropic muscle layers	15.63	8	Current is diverted away from deeper tissue layers by fat and longitudinal muscle electrical conduction
Muscle anisotropy removed	20.81	5	Removing muscle anisotropy increases current into deeper tissue layers by 30%
Fat and muscle anisotropy removed	45.49	2.9	Removing fat increases current into deeper tissue layers by 200%

Results

- Current decreases rapidly with distance from electrode
- The fat and skeletal muscle layers have an electric shell effect on currents that reach into deeper tissue layers (such as the heart):
  - The fat layer attenuates the electric field by at least 25 times, even under worst-case minimal thickness assumptions
  - Skeletal muscle preferred longitudinal (with the grain) electrical conduction diverts about 88% of the current away from deeper tissue layers

Results

- In the muscle layer:
  - the transverse current density is less than 15 mA/cm^2
  - the equivalent field strength is in the 15-30 V/cm range:
    > greater than 2.25 V/cm – threshold to capture motor neurons
    > but much lower than levels required for irreversible electroporation of skeletal muscle (1600 V/cm – Gehl et al. 1999)
    > Even the largest E field value in the model, 760 V/cm – in the fat layer, is less than irreversible electroporation thresholds

Methods: 3-D Refined FEM

Regions

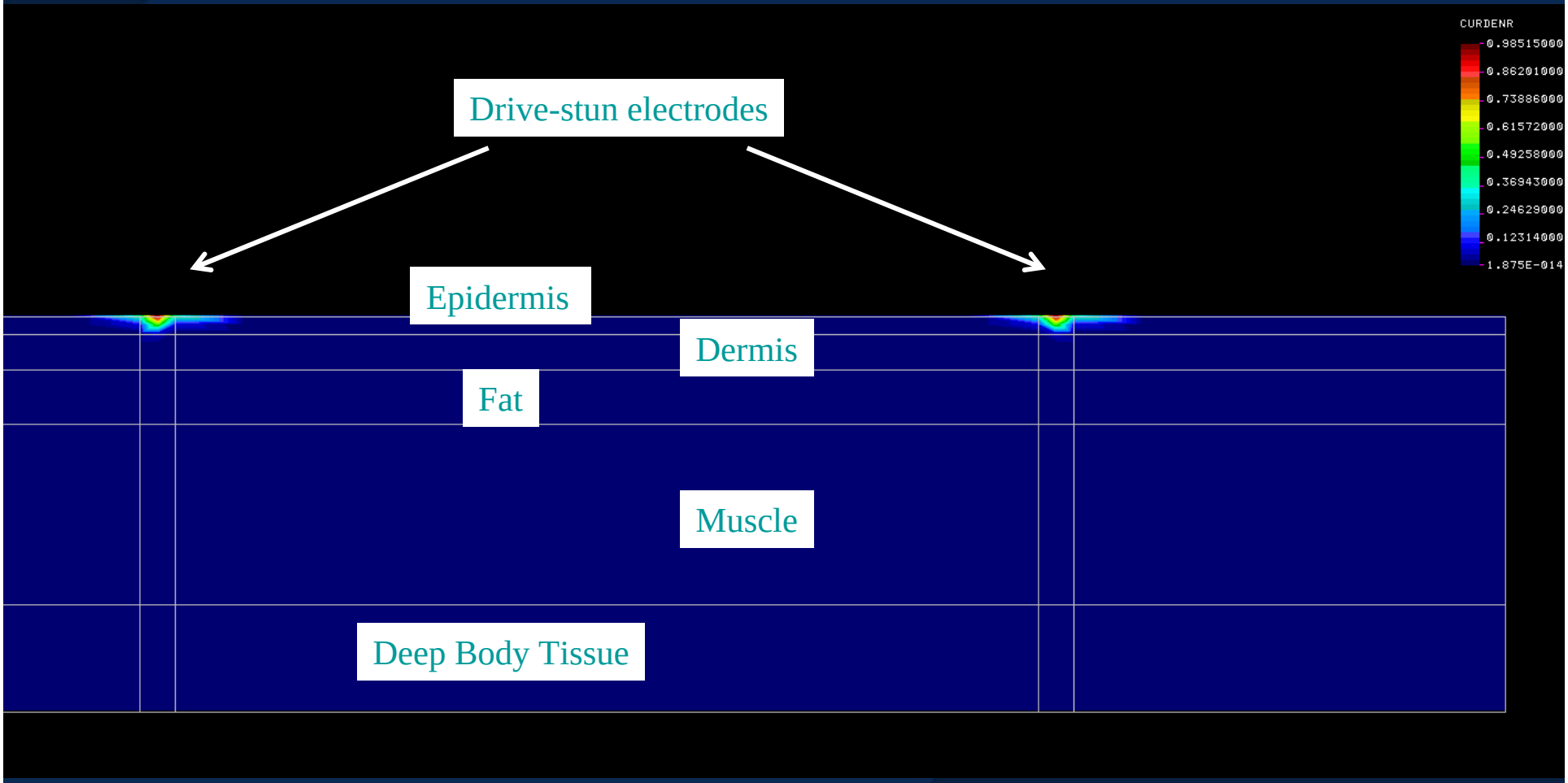
- Epidermis – 1 mm
- Dermis – 2 mm
- Fat – 3 mm (worst case scenario, average human fat layer thickness is 20 mm)
- Muscle – 10 mm
- Body tissue – 6 mm
- Electrodes –2-mm diameter
  - Modeled in drive-stun mode

- Nodes: 45900
- Elements: 41272 hexahedral elements
- Model: 25-cm long, 5-cm wide, 2.2-cm deep
- Electrodes: 5-, 15- or 20-cm apart
- Voltage boundary conditions: 1000 V
- Steady-state solution

Methods: 3-D Refined FEM

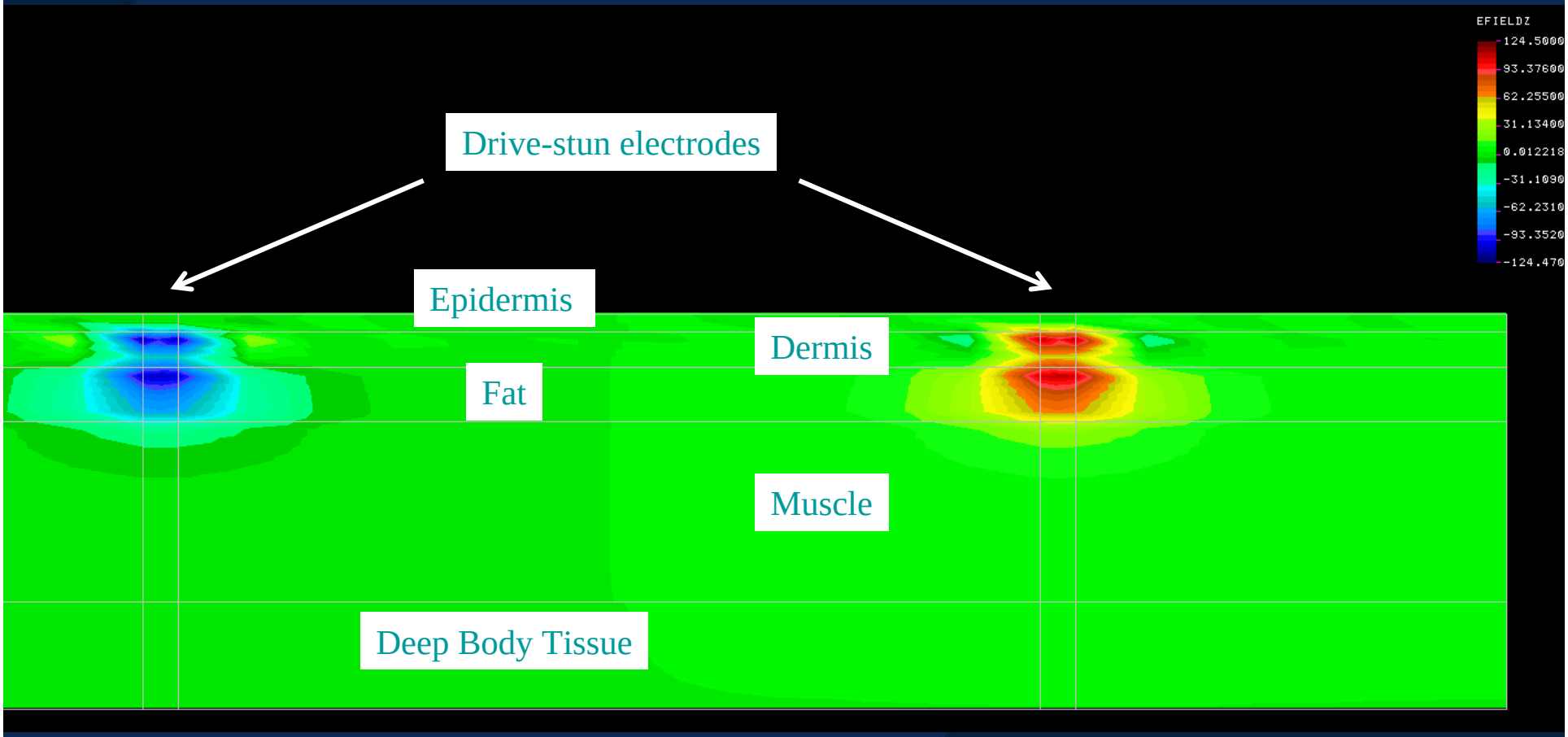
- Material properties (electrical resistivity)
  - Epidermis – 1 MΩ·cm
  - Dermis – 500 Ω·cm
  - Fat – 2200 Ω·cm
  - Muscle – anisotropic layer
    - $\rho x = \rho y = 200\ \Omega\cdot cm$ (longitudinal)
    - $\rho z = 1000\ \Omega\cdot cm$ (transversal)
  - Body tissue – 200 Ω·cm
  - Electrodes – 0.001 Ω·cm
- Goal: Study field and current distribution based on unrealistically thin layer of fat

Drive-stun mode – Current density distribution [A/mm^2]



- Current density decreases rapidly with distance from electrodes
- Levels in deep body tissue layers are well below VF thresholds (< 91 mA/cm^2)

Drive-stun mode – Electric field strength [V/mm]



- Electric field strength decreases rapidly with distance from electrodes
- Levels in skeletal muscle are well below electroporation thresholds (< 1600 V/cm)
- Levels in deep body tissue are below cardiac capture levels (< 2 V/cm)

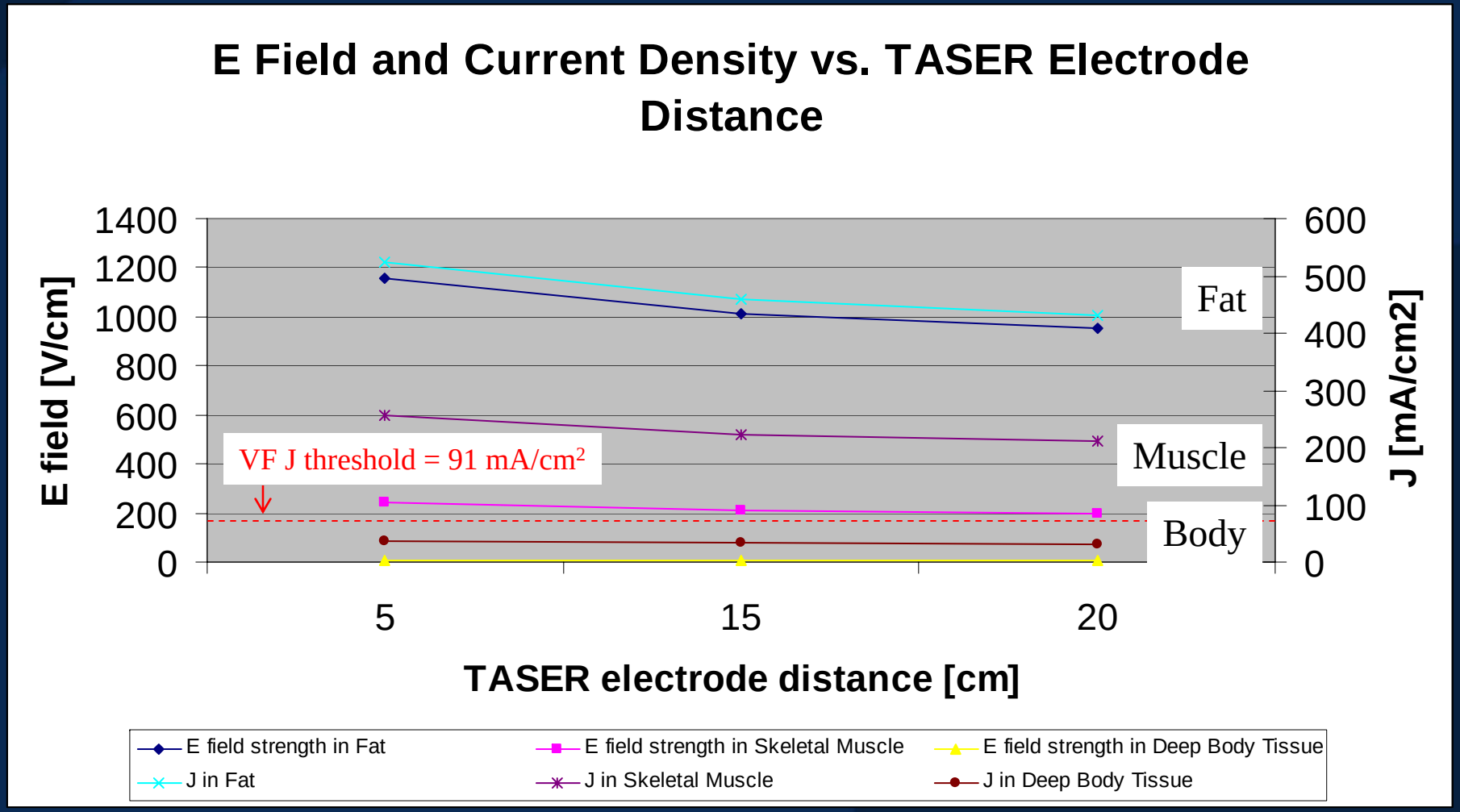
Drive-stun mode – E and J vs. depth

Tissue	Max E [V/cm]	Max J [mA/cm^2]
Dermis	1253	2506
Fat	1154	524
Skeletal Muscle*	241	255
Deep body tissue**	7	37

•At least E = 1600 V/cm required for irreversible electroporation

** At least J = 91 mA/cm^2 required for VF

Results – E & J vs. Electrode Distance



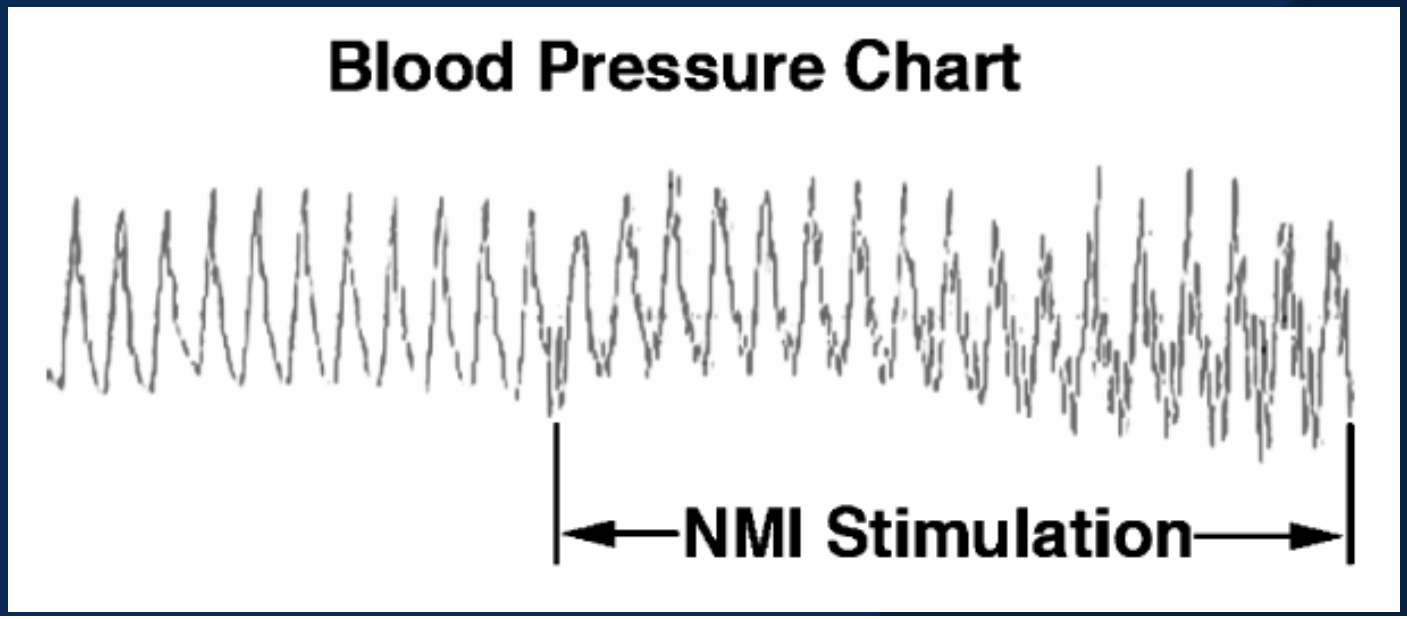
Conclusions

- TASER CEW J and E values for the muscle region higher than neuromuscular activation thresholds by a significant margin
- Even with a unrealistically thin layer of fat, worst-case skeletal muscle maximum values for TASER CEW J and E are lower, by at least a factor of ***seven***, than levels reported to produce permanent cellular electroporation or tissue damage
  - This safety margin would have been even higher had our models accounted for a nominal thickness of the fat layer
- Even with a unrealistically thin layer of fat, worst-case skeletal muscle maximum values for TASER CEW J and E fields and currents that reach into deeper layers of tissue are insufficient to trigger ventricular fibrillation
- TASER CEWs are efficient and safe in producing neuromuscular activation for temporary suspect incapacitation

Whole Body FEMs: Estimated TASER CEW Fields and Currents in Heart Volume

Methods

- Neuromuscular incapacitating (NMI) electrical discharges do not affect the systemic blood pressure
- After an average of 26 discharges per animal, all of the nine subject animals remain hemodynamically stable



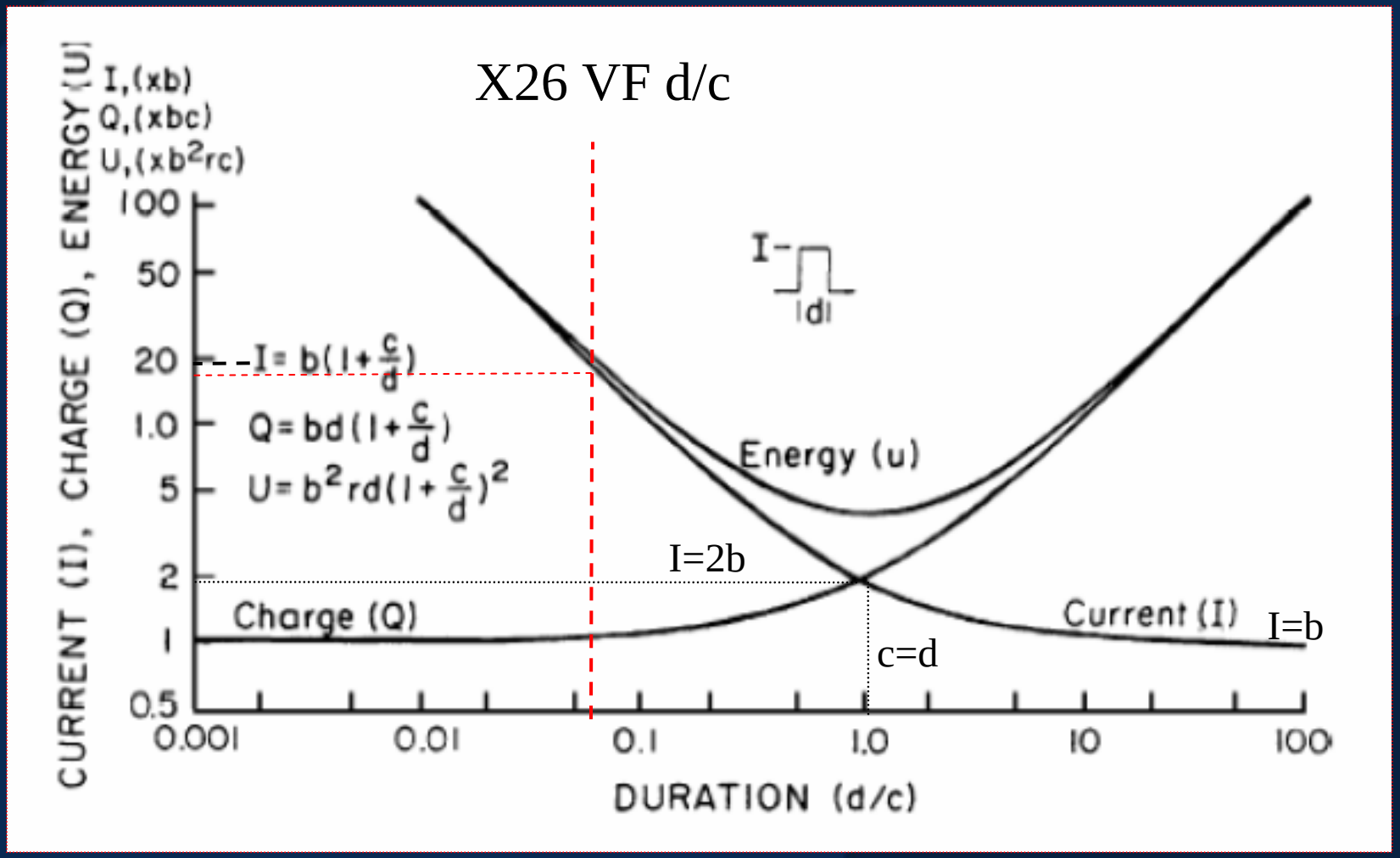
Methods: VF Rheobase

- **Sun et al. found that the rheobasic current density (i.e. for very long durations – or d/c > 10) required to induce ventricular fibrillation (VF) equals 7 mA/cm^2**
- **TASER current pulse width is about 100 μs, for the X26 model**

Methods: VF Chronaxie

- **The myocyte chronaxie is at least 1.2 ms, for a VF induction model**
- **The corresponding d/c value is 0.08, for VF (X26) – c/d ~ 12**
- **As such, the current density threshold required to induce VF is about 91 mA/cm^2 (91 = 7*(1+12))**
- **FEM of the human body to estimate the current density distribution**

Methods: X26 VF Threshold



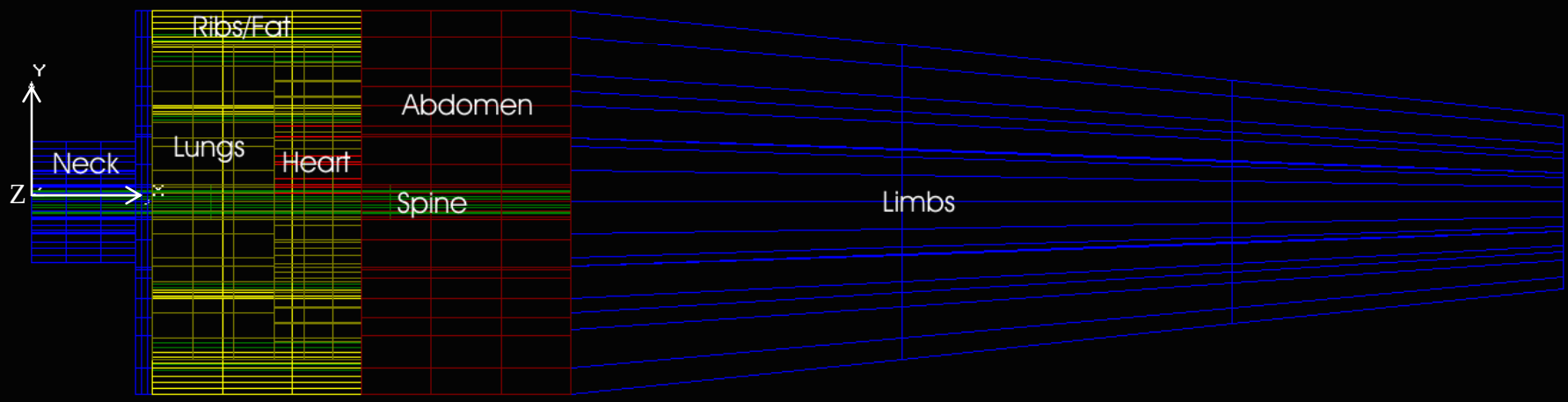
3-D Finite Element Body Model

- **Regions (see Tchou TTE model)**
  - Muscle (neck, shoulder, limbs)
  - Heart
  - Bone (spine, ribcage)
  - Lungs
  - Skin/Fat (~ 20-30 mm thick)
  - Abdomen
- **Elements: 8640 hexahedral elements**
- **Model: human body, about 176-cm long**
- **Electrodes: 8 cm apart, applied onto the body surface**
- **Applied voltage: 1000 V**

3-D Finite Element Model

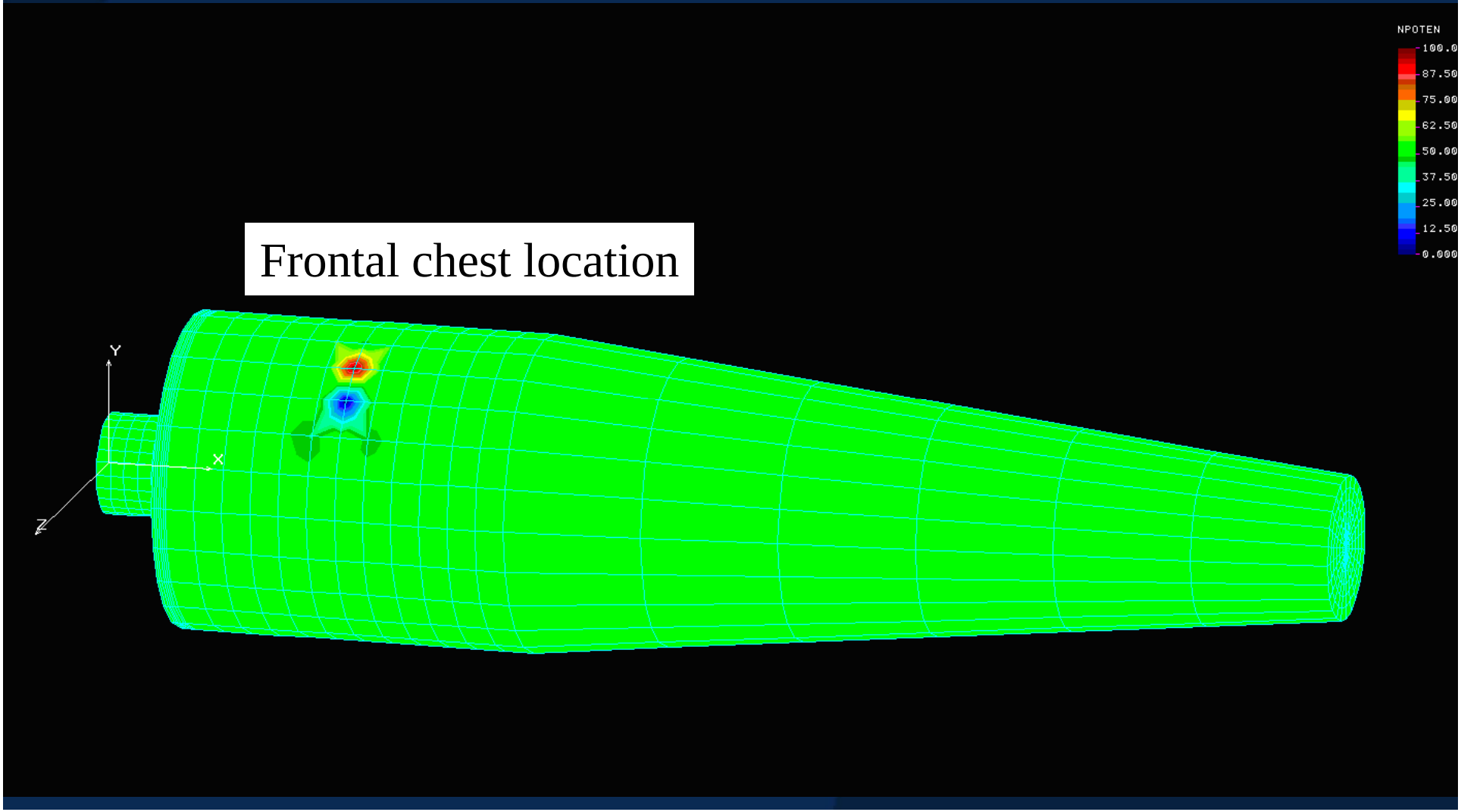
- **Material properties (electrical resistivity)**
  - Epidermis – 1 MΩ·cm
  - Dermis – 500 Ω·cm
  - Fat – 2200 Ω·cm
  - Muscle – anisotropic layer
    - $\rho x = \rho y$ = 200 Ω·cm (longitudinal)
    - ρz = 1000 Ω·cm (transversal)
  - Electrodes – 0.001 Ω·cm

FEM – Human Body 176-cm long

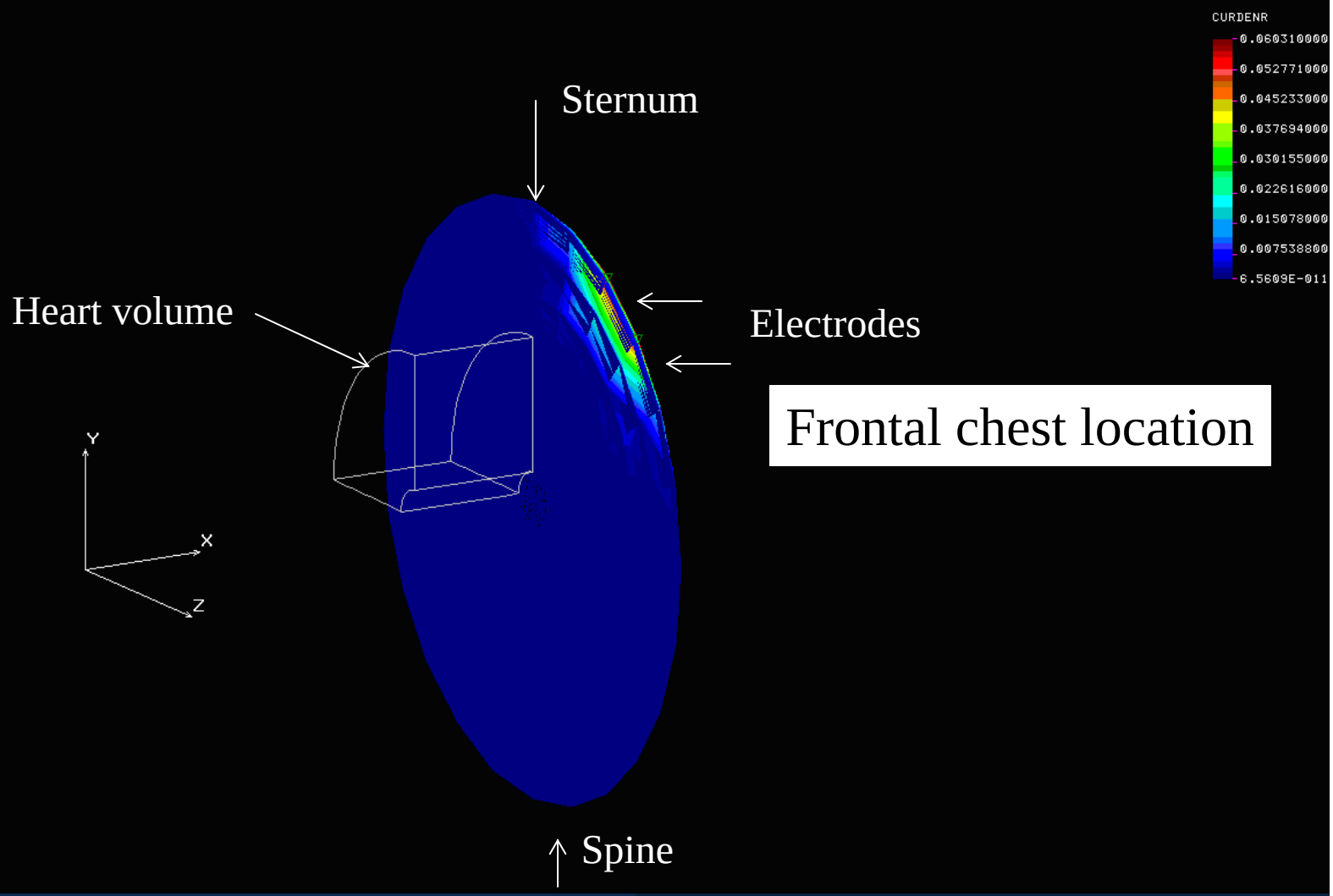


FEM – Voltage distribution [V]

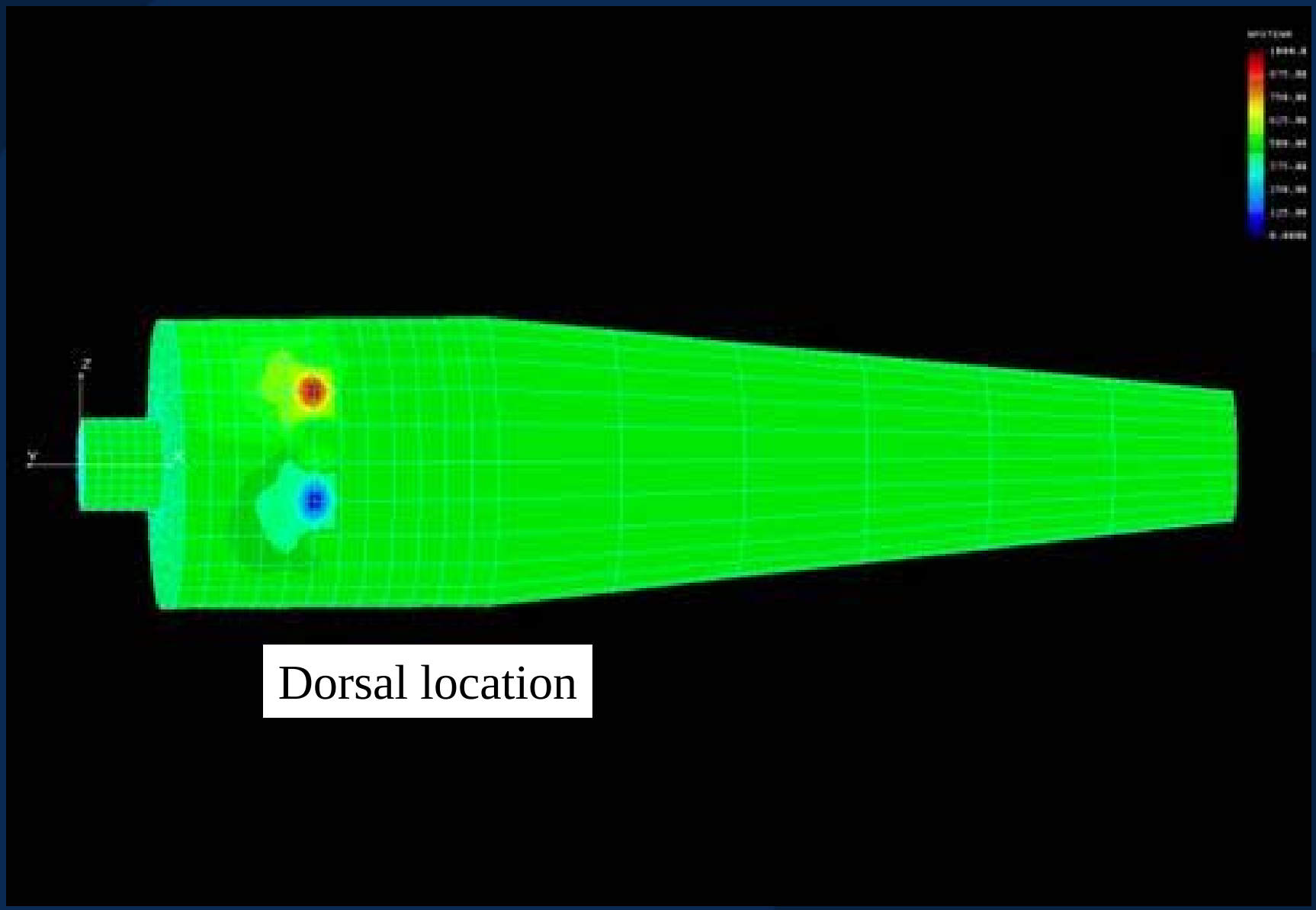
*** multiply by 10 for actual voltage values**



FEM – Heart current density distribution [A/cm^2]

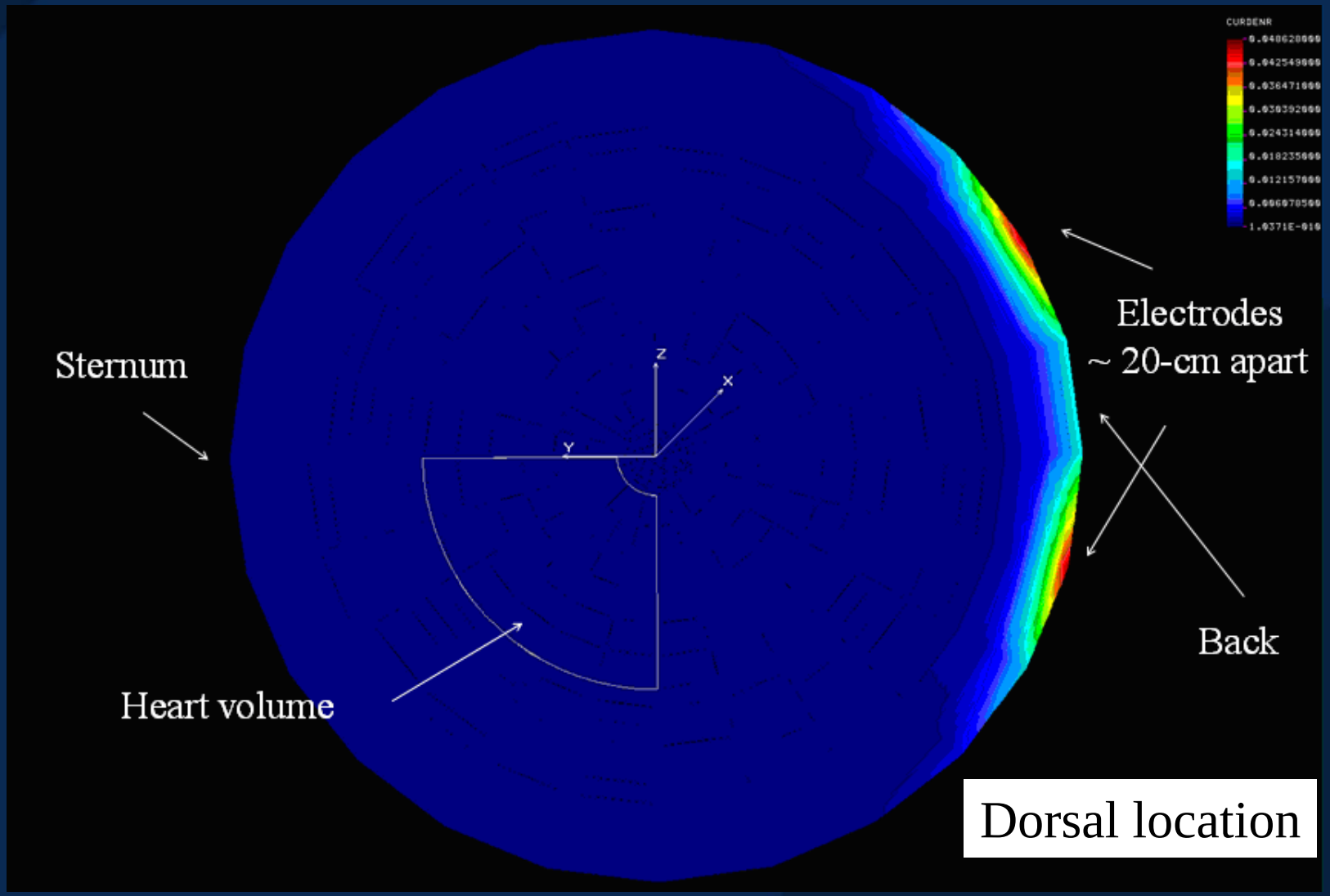


FEM – Voltage distribution [V]



Dorsal location

FEM – Heart current density distribution [A/cm^2]



Maximum heart current density and safety margins vs. TASER electrode locations

Electrode separation and position	Maximum current density in the heart	Safety margin with respect to VF threshold	Safety margin with respect to capture threshold **(capture based on E of 2 V/cm)**
8” – over dorsal area	0.064 mA/cm^2	1421 times	69 times
8” – left nipple to left thigh	0.24 mA/cm^2	379 times	18 times
3” – frontal chest, straight over heart	2.7 mA/cm^2	34 times	1.7 times

Results

- **For point-type electrodes, the skin/fat and muscle layers significantly attenuate the current before it reaches the epicardium**
  - Current density at electrode 600 mA/cm^2
  - Current density underneath skin/fat&muscle 20-40 mA/cm^2
- **The maximum TASER current density in the heart is 2.7 mA/cm^2**
- **The threshold required to induce VF is 91 mA/cm^2**
- **The numerically estimated safety margin is larger than 34 times (91/2.7)**

Conclusions

- **The fat layer significantly reduces the current that reaches deeper into the body**
- **TASER currents are much lower than levels required to trigger ventricular fibrillation**
- **These numerical models estimate that TASER devices are effective and safe**

References

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Summary of probabilistic analysis of TASER-induced VF

Risk assessment of theoretical effects of TASER CEW currents

- **TASER International Inc. reported that CEWs were used in:**
  - More than 232,000 human volunteers
  - More than 383,000 human suspects during actual law enforcement field deployments
- **No direct cardiac or muscular damage reportedly associated with TASER CEW usage above**
- **Overall theoretical critical risk of using TASER CEWs is estimated at less than 1/(232000+383000) = 0.0000016**

EN 60601-1: VF risk rational

- **The allowable value of PATIENT LEAKAGE CURRENT for TYPE CF APPLIED PARTS in NORMAL CONDITION is 10 µA which has a probability of *0.002* for causing ventricular fibrillation or pump failure when applied through small areas to an intracardiac site.**

- **Even with zero current, it has been observed that mechanical irritation can produce ventricular fibrillation. A limit of 10 µA is readily achievable and does not significantly increase the risk of ventricular fibrillation during intracardiac procedures.**

EN 60601-1: VF risk rational

Note – Refer to original papers by Starmer and Watson for interpretation of data.

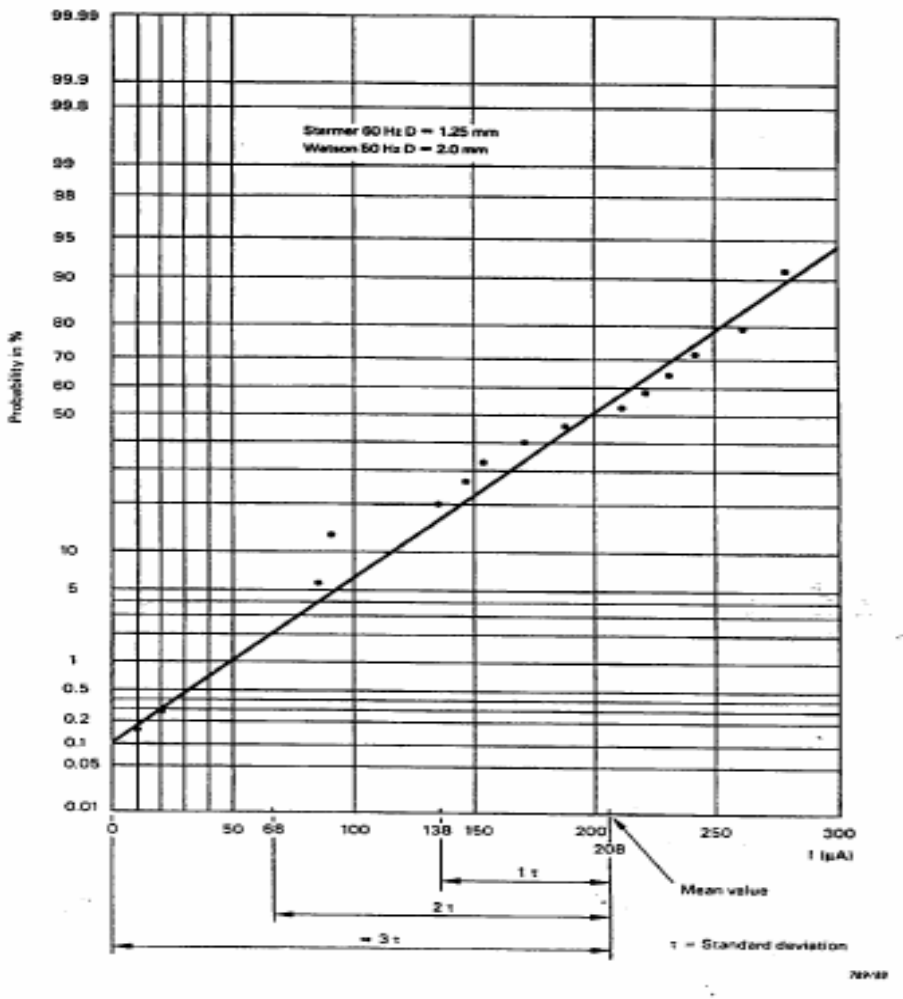


FIG. A1. — Probability of ventricular fibrillation.

EN 60601-1: VF risk implications

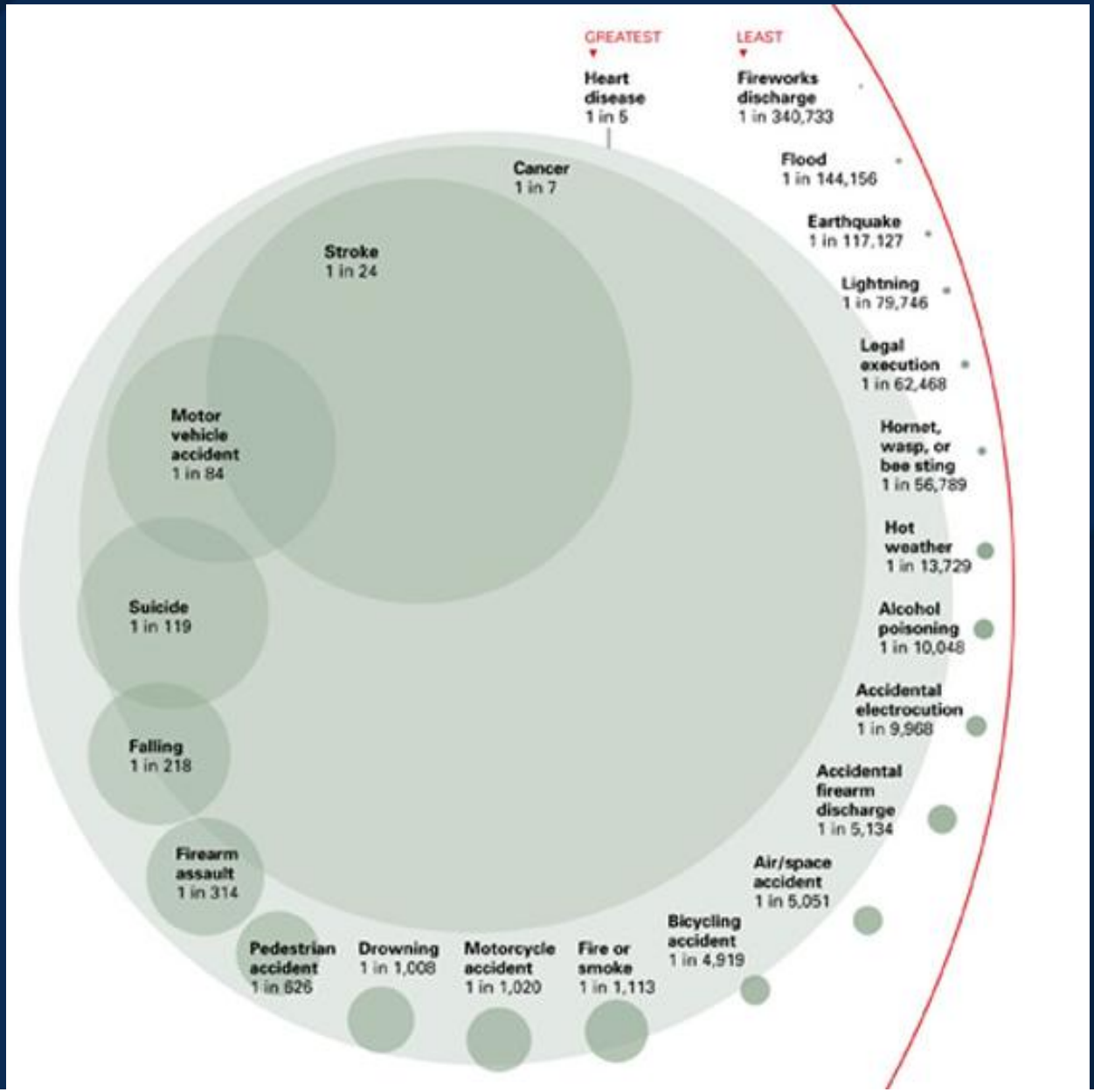
- **US FDA certifies electrical medical devices as safe for intracardiac use if they comply with the patient leakage current limit above.**
- **Intracardiac procedures carry the highest risk.**
- **By accepting requirements of EN60601-1, the FDA implicitly accepts that *0.002* represents an extremely low probability of triggering VF.**

- **The FDA-accepted risk level of 0.002 is 1250 times higher than the probability estimates for VF induction by TASER CEW (1250=0.002/0.0000016) .**

Risks of common daily-life activities

	MALES ONLY, ALL AGES		
	France 1996	Italy 1996	UK 1997
Total deaths (000)	28,423	27,804	28,990
	Death per 100,000 per year		
Cardiovascular disease	280.2	401.2	430.0
Cancer	306.8	311.0	275.0
Cerebrovascular disease	63.5	102.7	85.9
Pneumonia	27.9	12.2	84.0
Diabetes	10.1	24.0	10.5
Nutritional deficiency	2.6	0.1	0.1
Accidents (all)	57.2	45.6	24.8
Road Traffic Accident	19.4	21.9	9.1
Drowning	1.6	1.3	0.7
Fire	1.1	0.7	1.1

“Ways to go” – National Geographic August 2006



Probabilities of risk encountered in common daily-life activities

- **Fireworks discharge death rate in the US 2003 was 0.0000029.**
- **The rate of drowning in France in 1996 was 0.000016.**
- **Yearly compounded probability of dying while crossing the street of about 0.0000442.**
- **The average rate of car accident death in Italy in 1996 was 0.000219.**
- **Preoperative death in patients admitted for implantation of cardiac stimulators is a probability of 0.018.**

- **All these vs. an worse-case theoretical probability of 0.0000016 for damage induced by TASER CEWs.**

Probabilities of risk

Event	Theoretical death probability	Theoretical death per 100000
EN60601-1 risk level	0.002	200
Car accident in Italy	0.000219	21.9
Drowning in France	0.000016	16
Fireworks	0.0000029	2.9
TASER CEWs	0.0000016	1.6

Conclusion

- **Use of TASER CEW devices involves a risk that is lower or comparable to risk levels accepted by the FDA for intracardiac medical devices or risks levels of daily-life activities.**