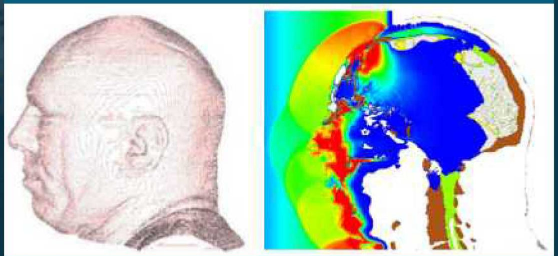
SAND2019-1068PE

Geometric Framework for FE and FV Analyses of Blunt and Blast Insults to the Sandia Head/Neck Model



PRESENTED BY

Chad B. Hovey

Cooper, Dederman, Haniff, Ruggirello, Terpsma

Terminal Ballistics Technology Department 5421

www.sandia.gov/biomechanics February 5, 2019

SAND____-____ PE

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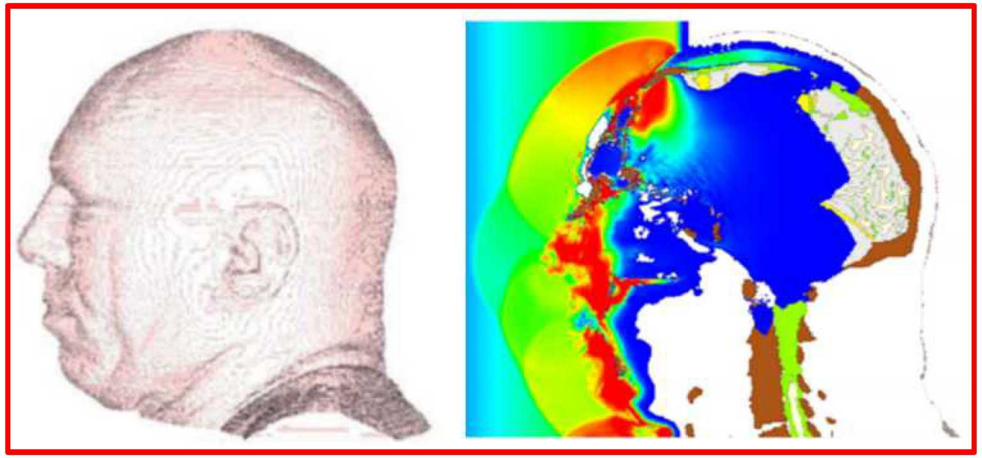
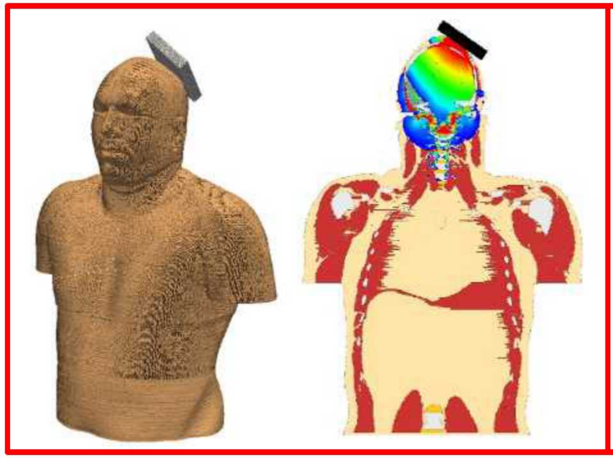
$$R(u) = F_{iner}(\ddot{u}) + F_{int}(\dot{u}, u) - \boxed{F_{ext}} = 0$$

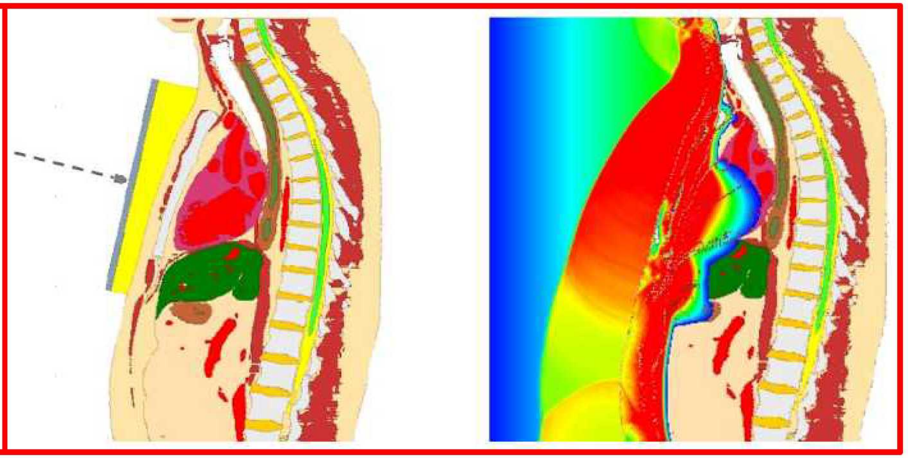
Blast



Blunt Impact



Ballistics



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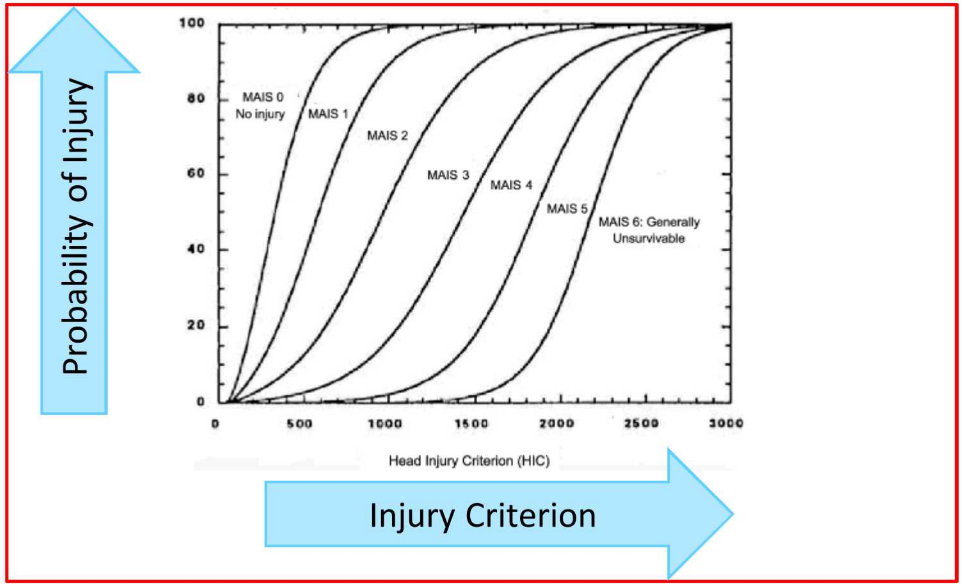
$$R(u) = F_{iner}(\ddot{u}) + F_{int}(\dot{u}, \boxed{u}) - F_{ext} = 0$$

Response

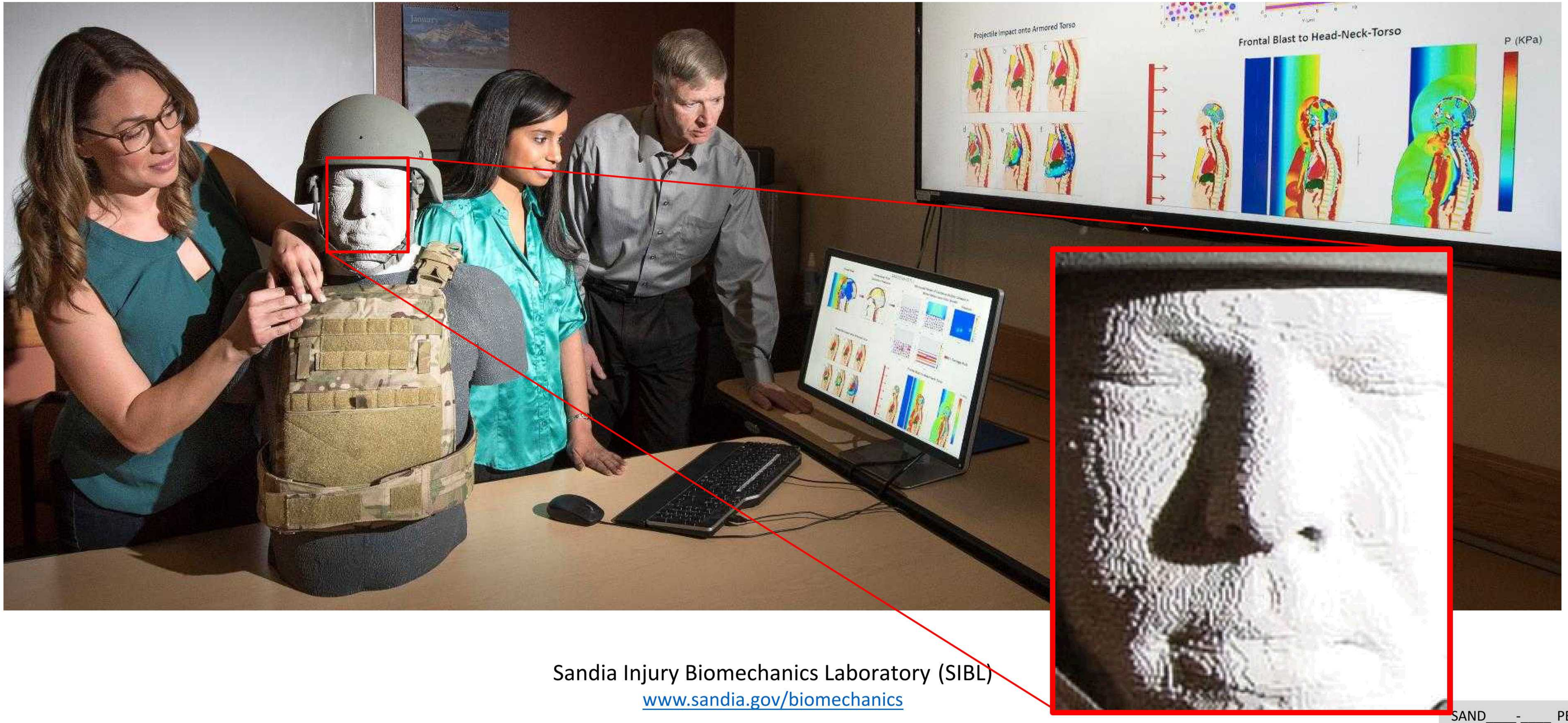
Injury Risk

Injury Criteria



Geometric Models

$$R(u) = \boxed{F_{iner}}(\ddot{u}) + \boxed{F_{int}}(\dot{u}, u) - F_{ext} = 0$$



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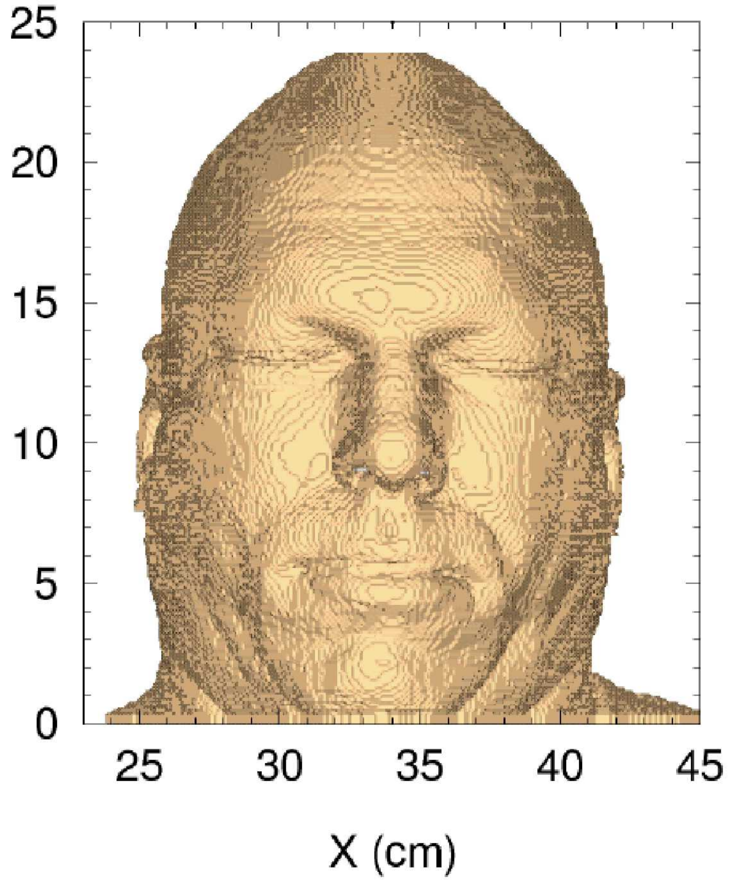
U.S. National Library of Medicine

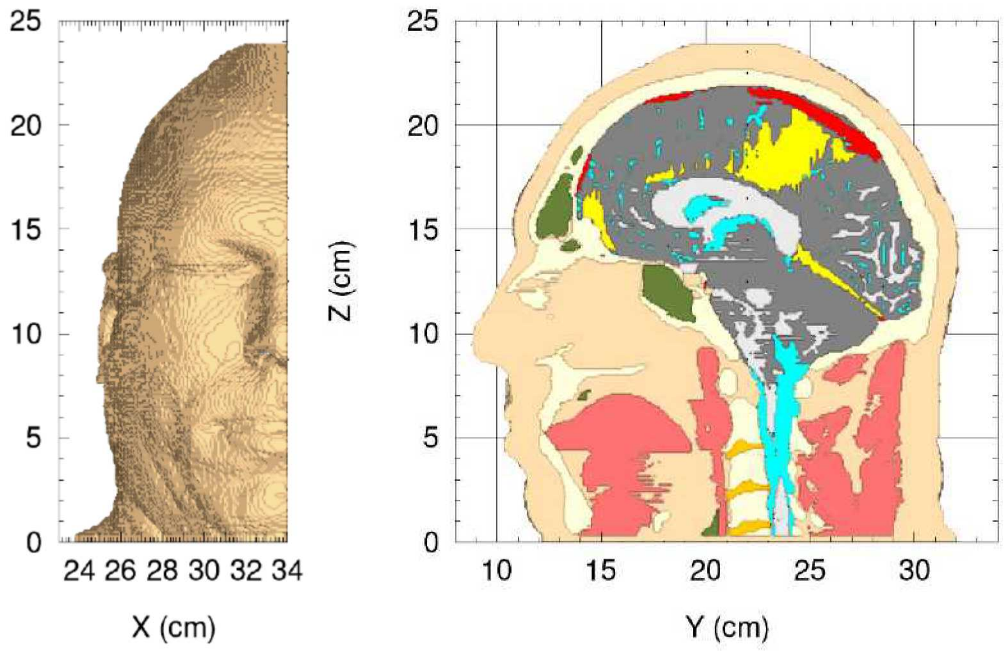
CT and digital photography scan entire body
- full body 1,871 axial slices at 1 mm intervals
- CT: 512 x 512 pixels; 12 bit gray
- Photo: 4,096 x 2,700 pixels; 24 bit color

MR head and neck
- axial slices at 4 mm intervals
- 256 x 256 pixels; 12 bit gray

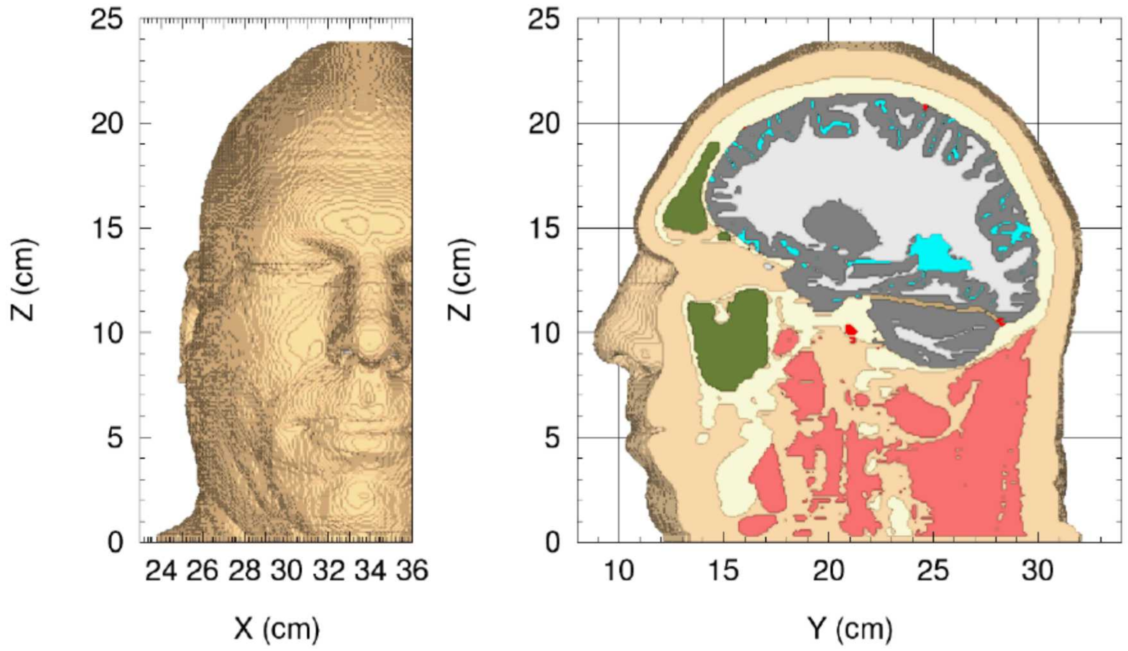
FV Bob



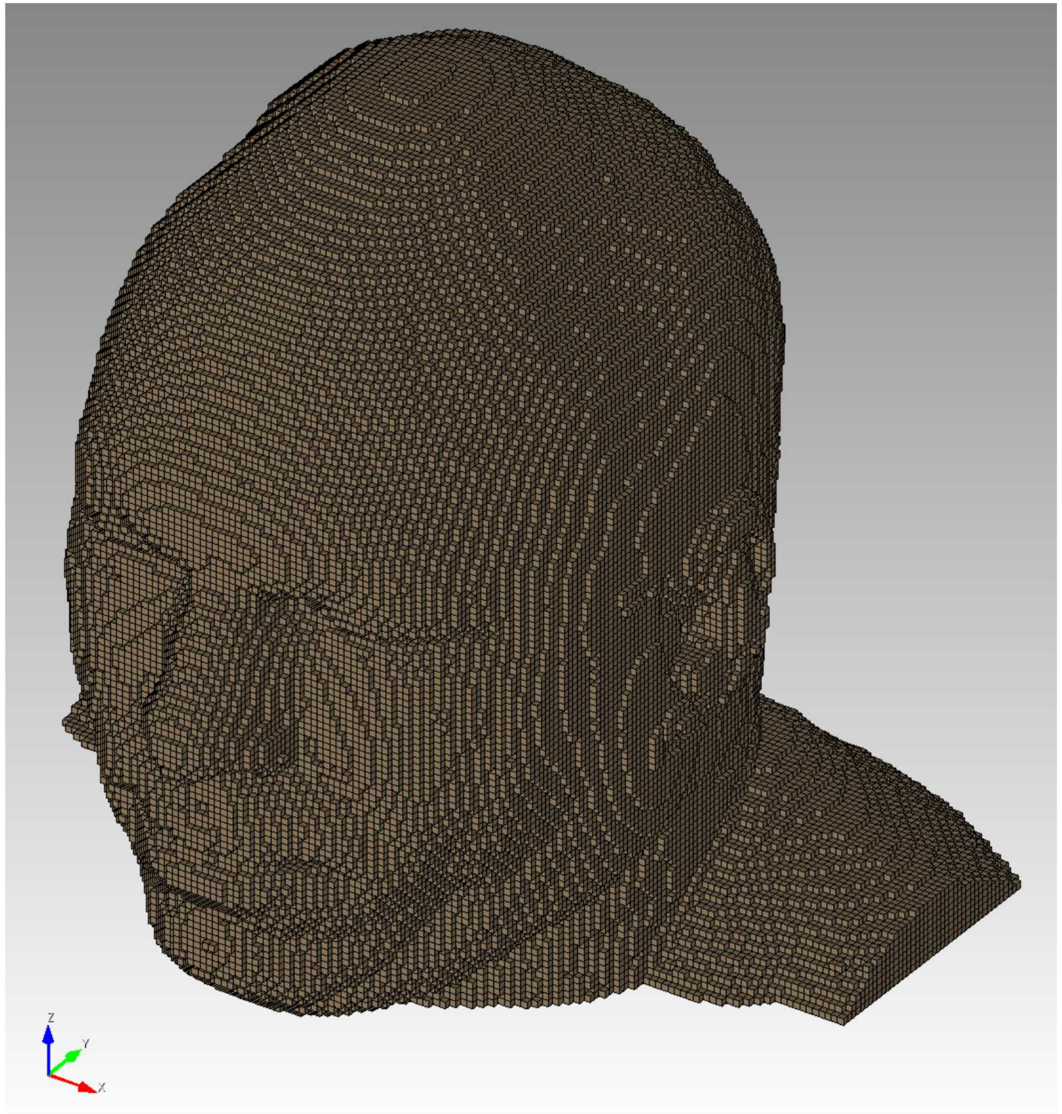
Mid-sagittal
X = 340 mm = 34.0 cm



Mid-sagittal + 2 cm offset
X = 360 mm = 36.0 cm



Block	Anatomy	FV Bob	FE Bob	
			Coarse (2 mm) hex	**Fine** Fine (1 mm) hex
1	bone	729 cc	733 cc; 91,562 hex	729 cc; 728,704 hex
2	disc	6 cc	6 cc; 653 hex	6 cc; 5,552 hex
3	vasculature	29 cc	28 cc; 3,473 hex	29 cc; 29,038 hex
4	airway_sinus	94 cc	94 cc; 11,805 hex	95 cc; 94,577 hex
5	larynx	< 1 cc	< 1 cc; 3 hex	< 1 cc; 31 hex
6	membrane	21 cc	22 cc; 2,712 hex	21 cc; 21,234 hex
7	CSF	78 cc	44 cc; 5,453 hex	78 cc; 77,552 hex
8	white matter	507 cc	503 cc; 62,814 hex	507 cc; 507,495 hex
9	gray matter	791 cc	829 cc; 103,597 hex	791 cc; 790,814 hex
10	muscle	912 cc	919 cc; 114,855 hex	912 cc; 912,150 hex
11	skin	2,266 cc	2,259 cc; 338,106 hex	2,265 cc; 2,487,080 hex
	Total	**5,433 cc**	**5,434 cc; 735,033 hex 766,021 nodes**	**5,432 cc; 5,654,227 hex 5,778,584 nodes**



FV Bob to FE Bob

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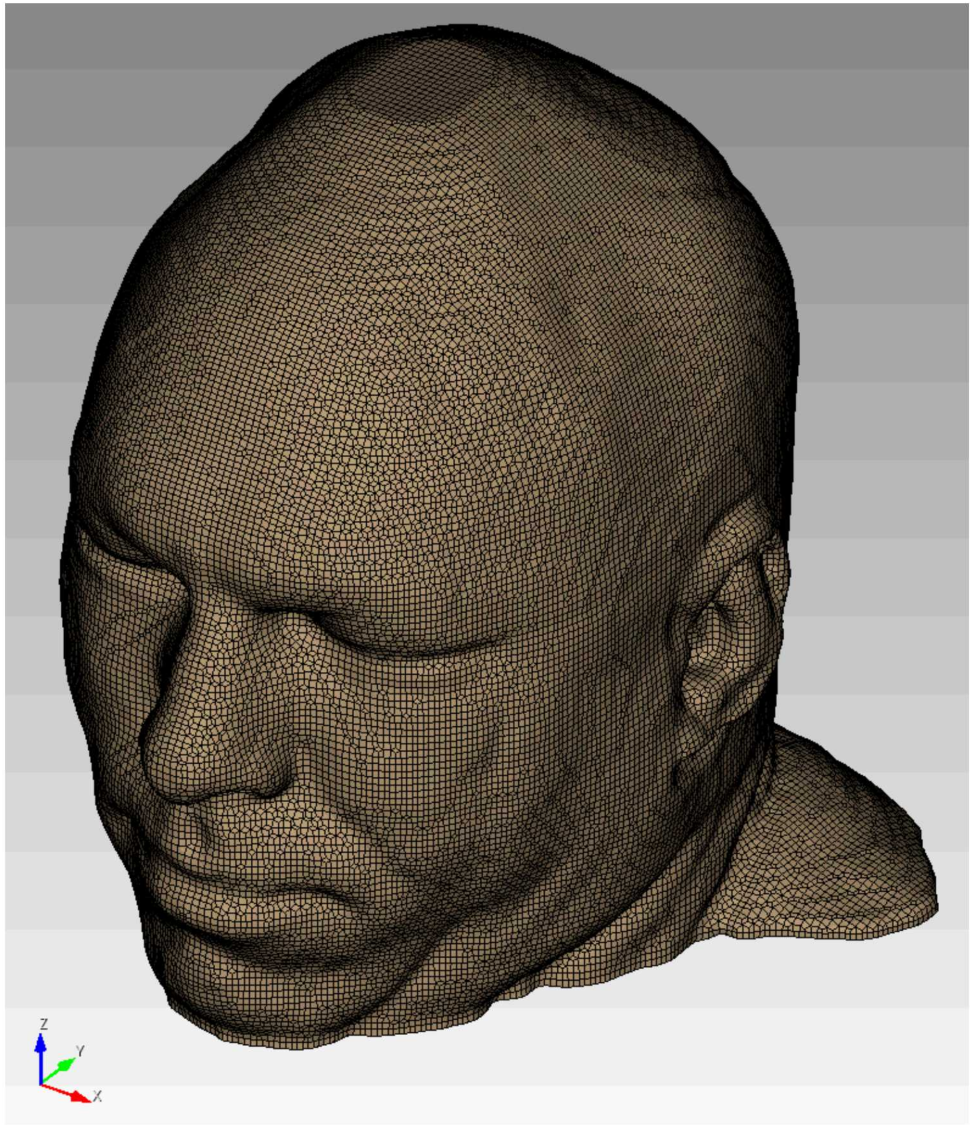
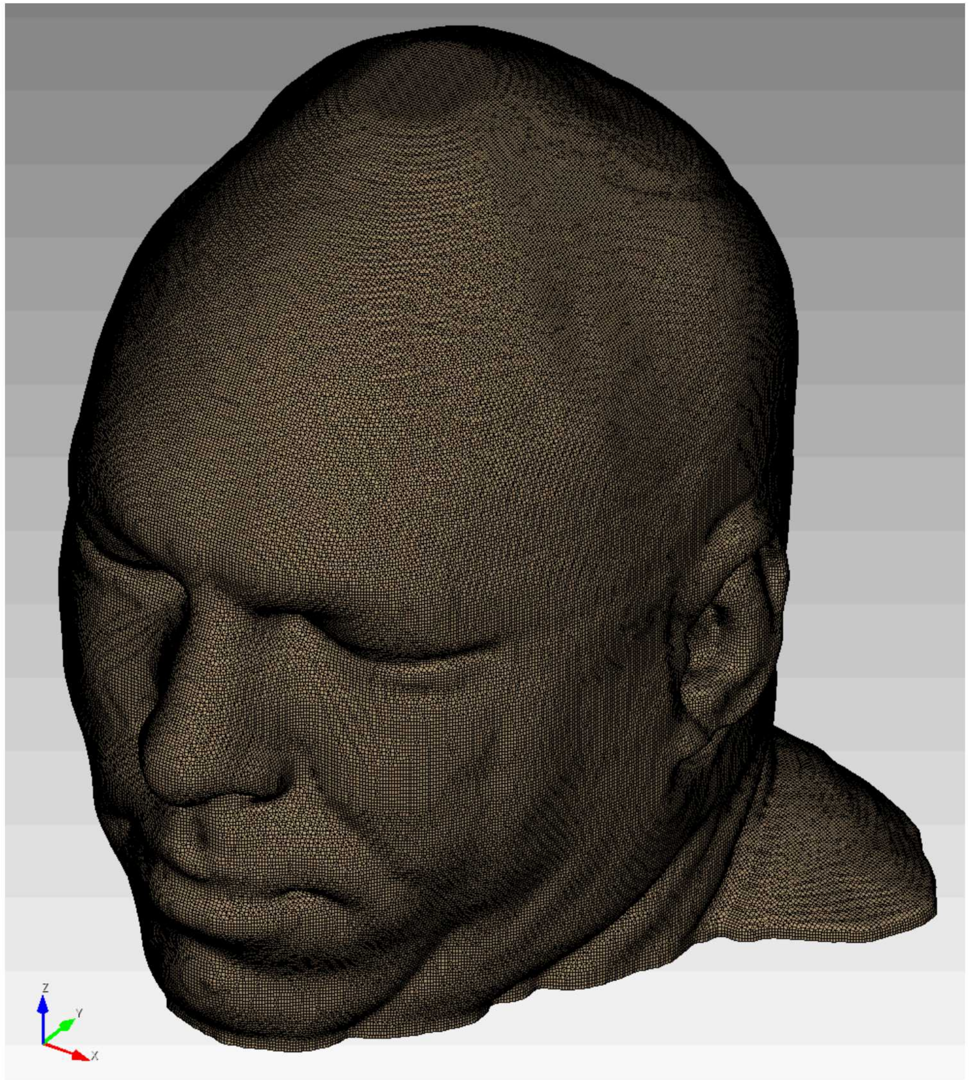
FE Bob Coarse (2 mm)



FE Bob Fine (1 mm)



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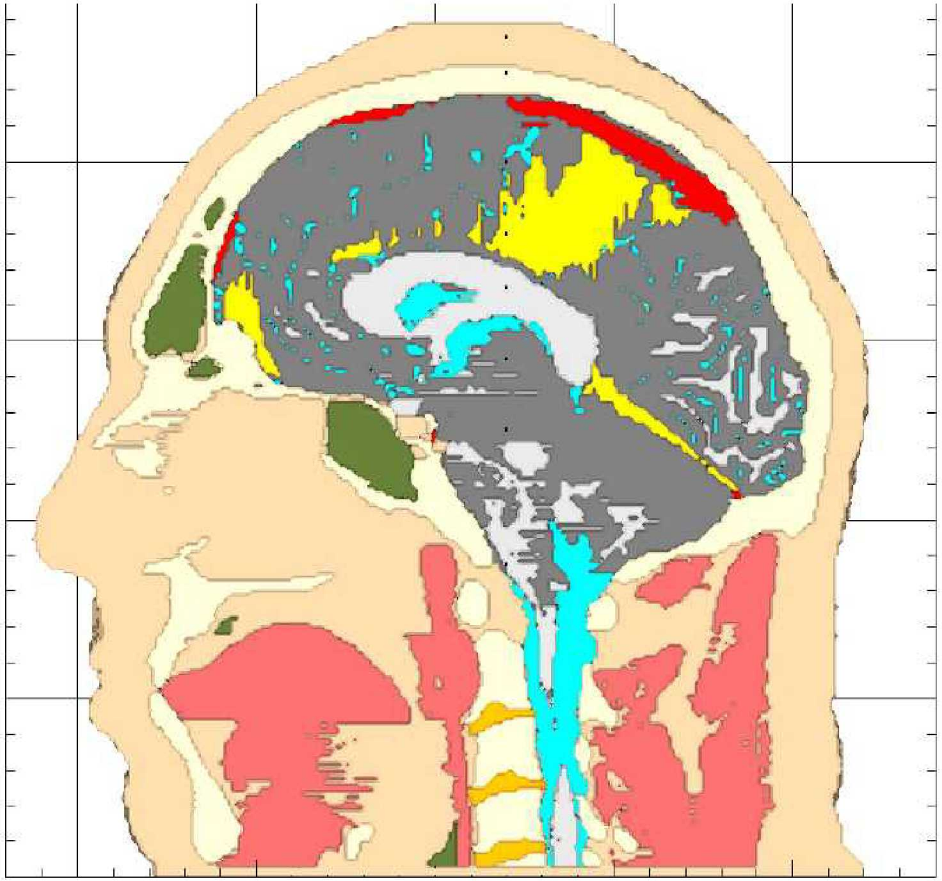
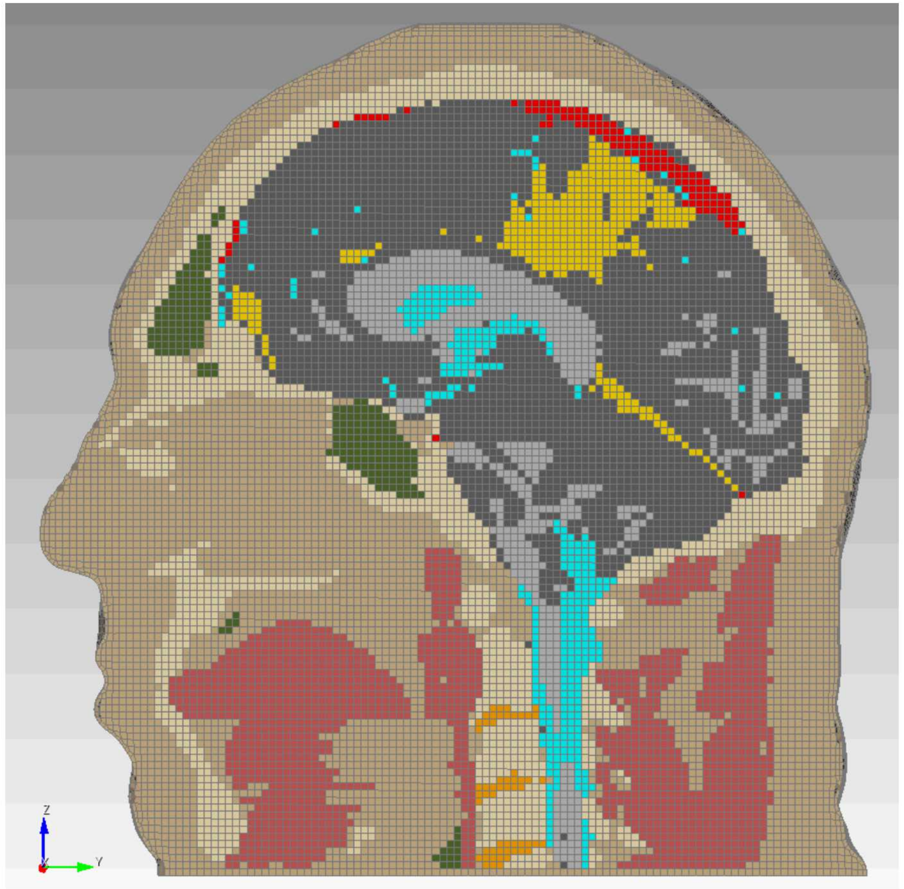
FV Bob (1 mm)



FV Bob Coarse (2 mm)



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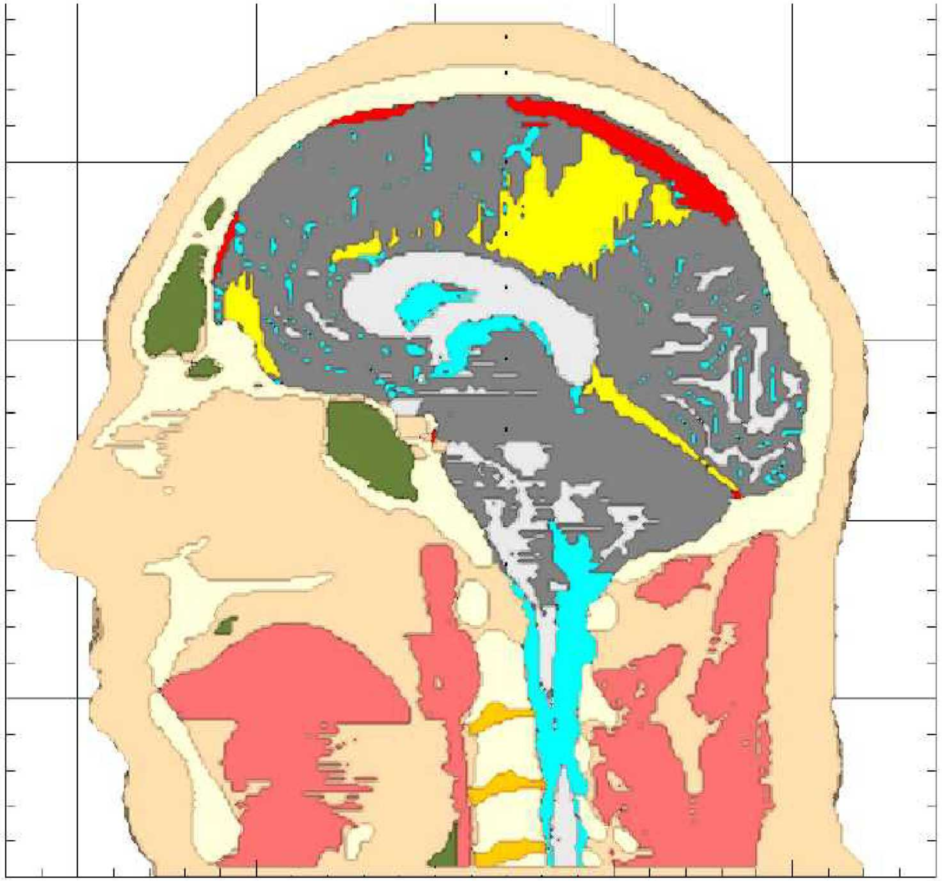
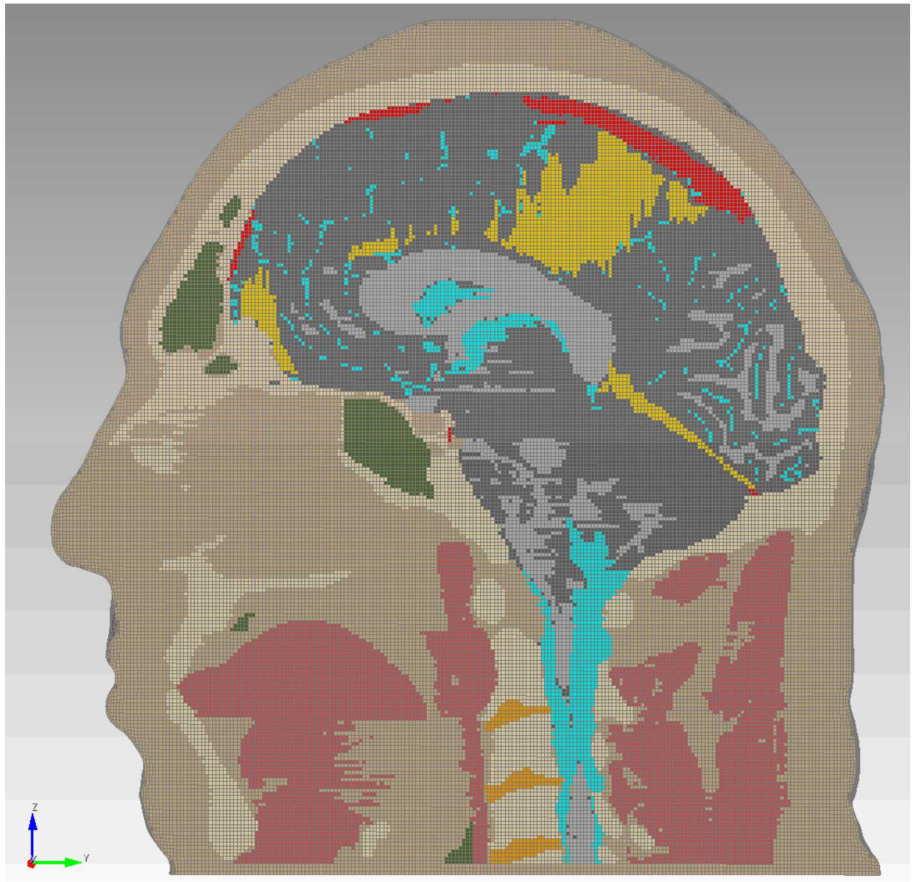
FV Bob (1 mm)



FV Bob Fine (1 mm)



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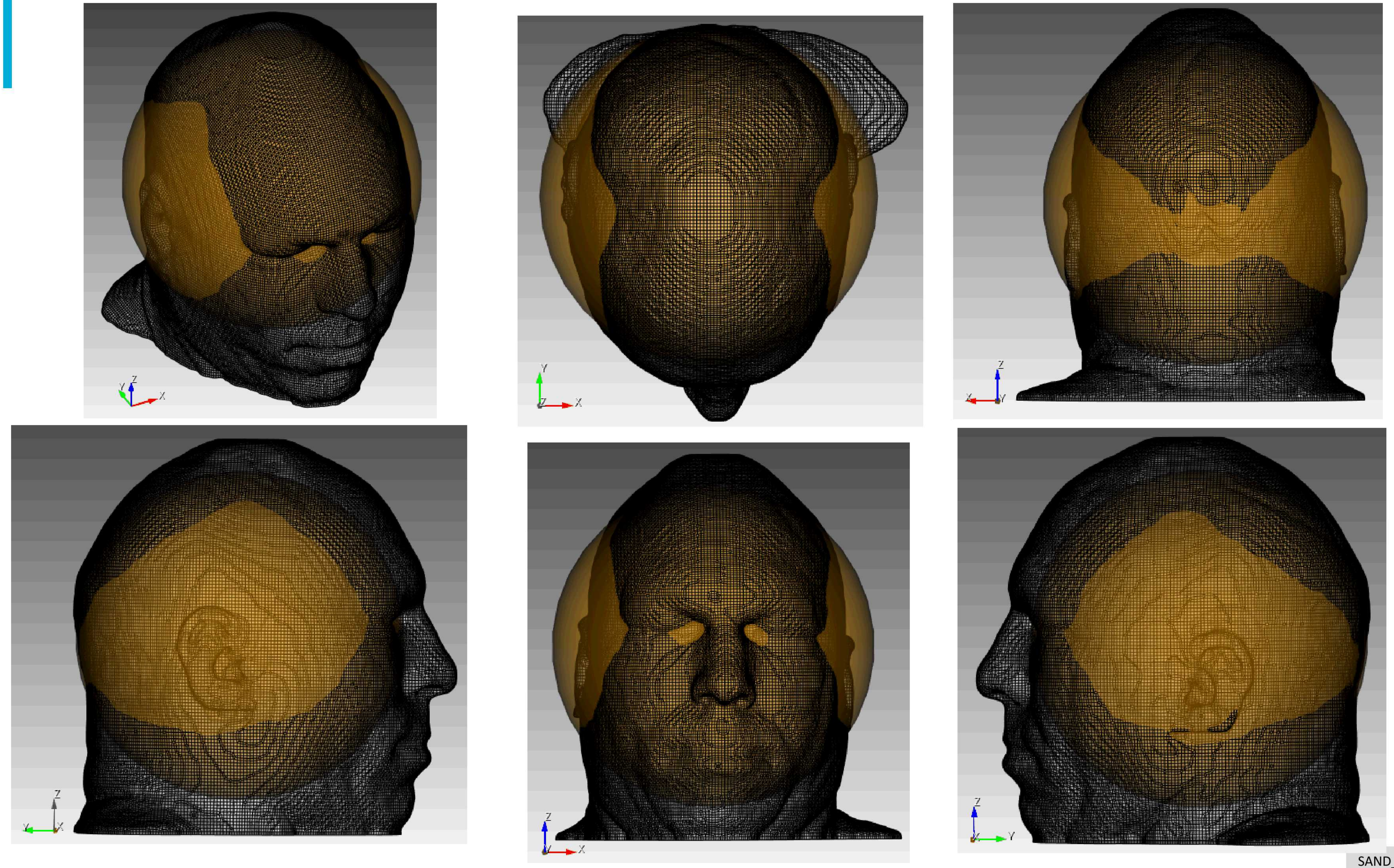

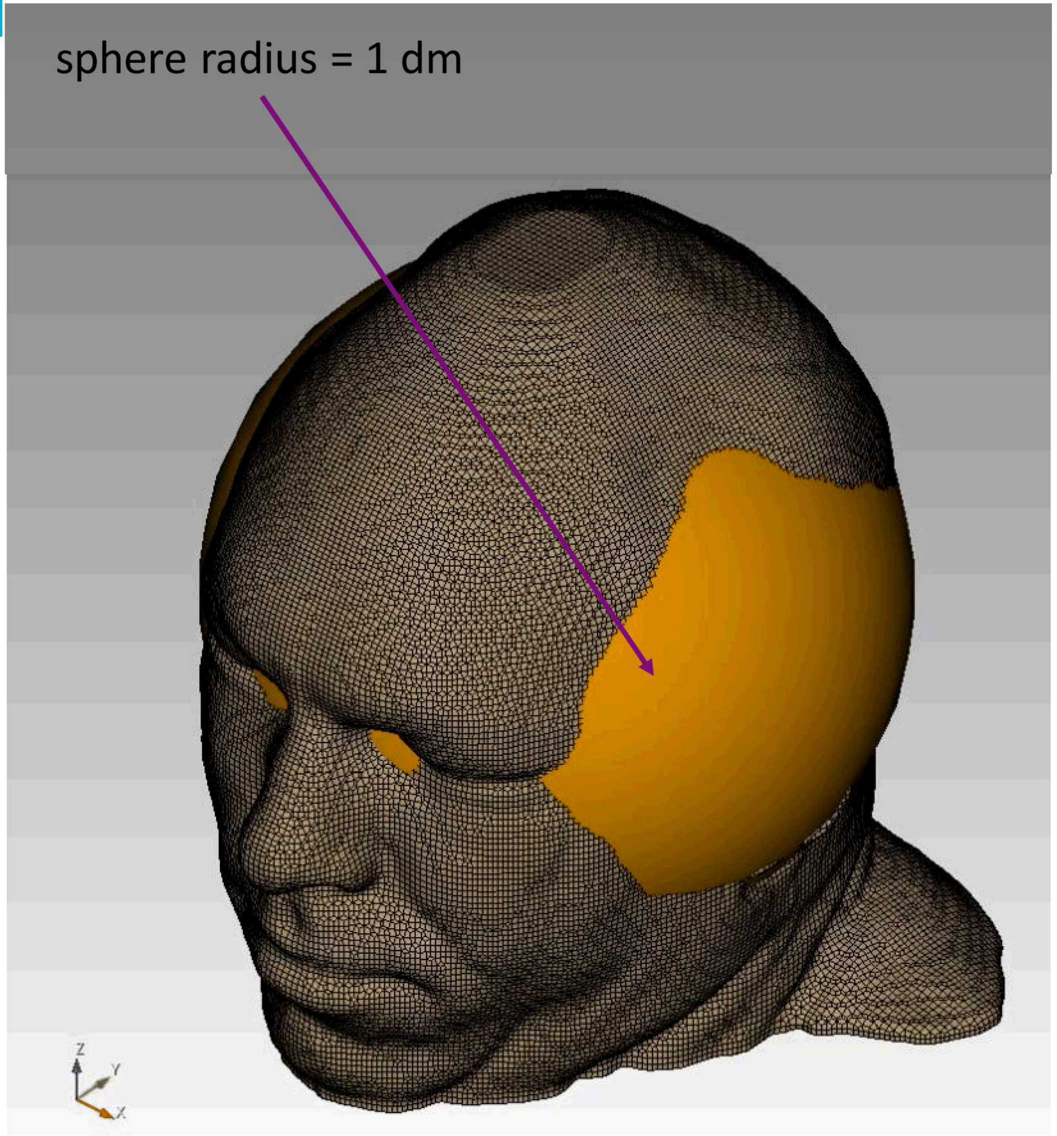

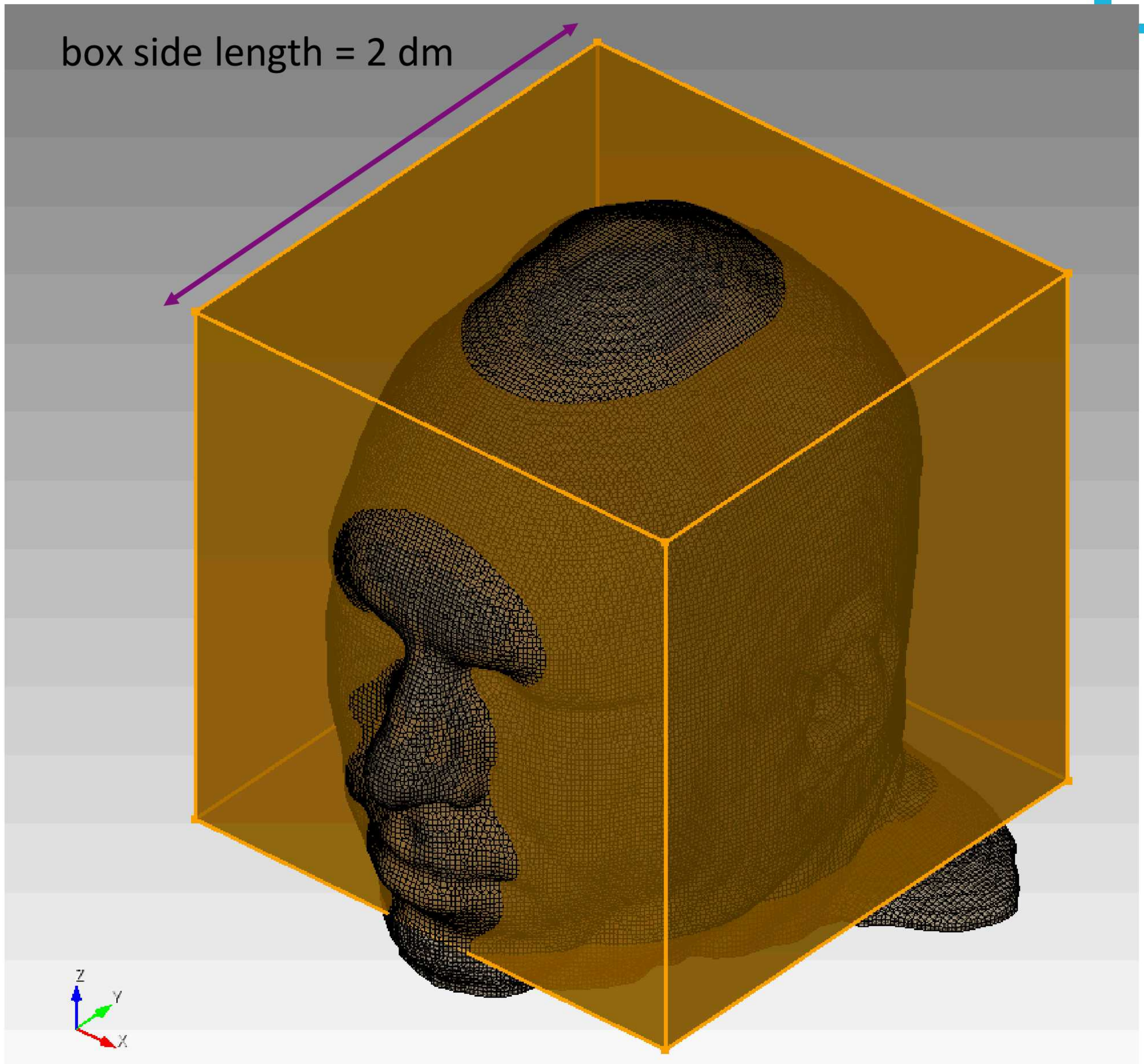

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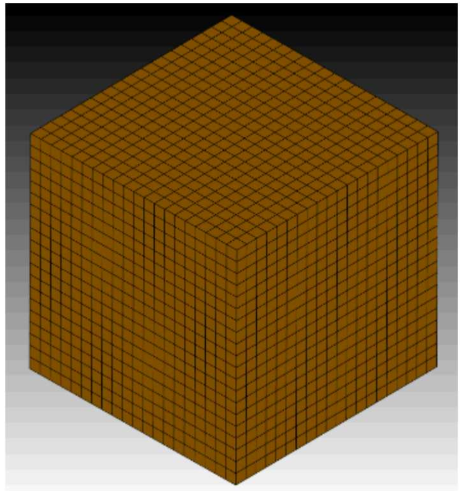
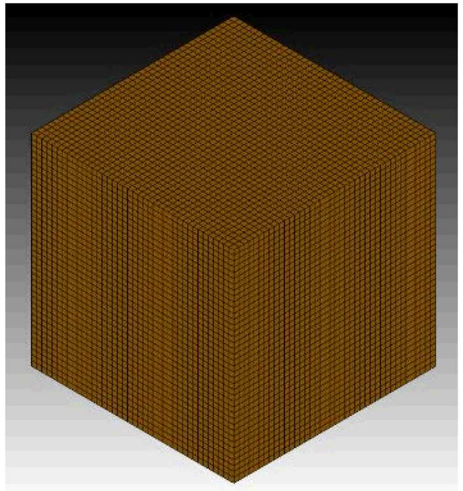
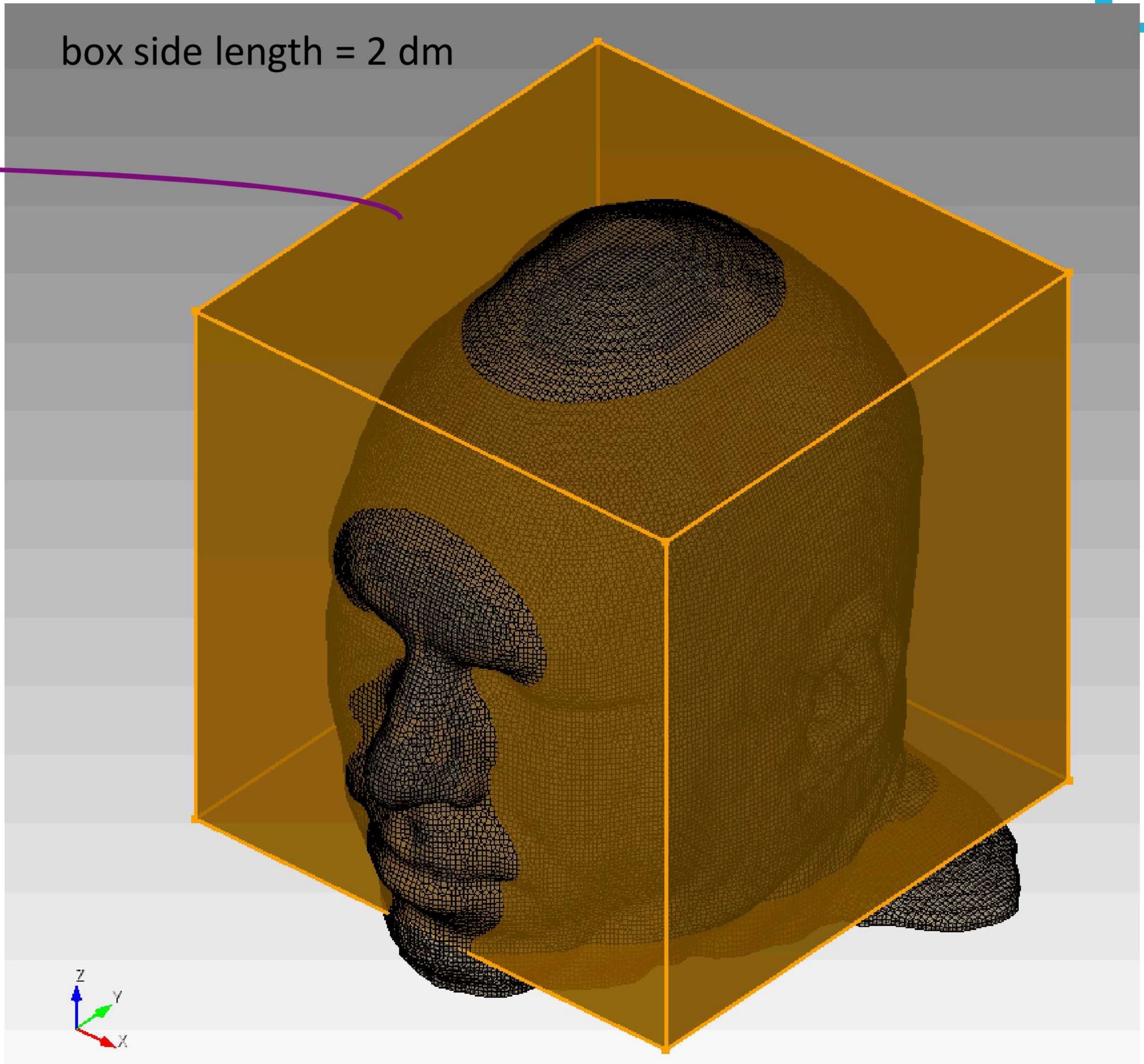
element length = 1 cm
8,000 elements



element length = 0.5 cm
64,000 elements





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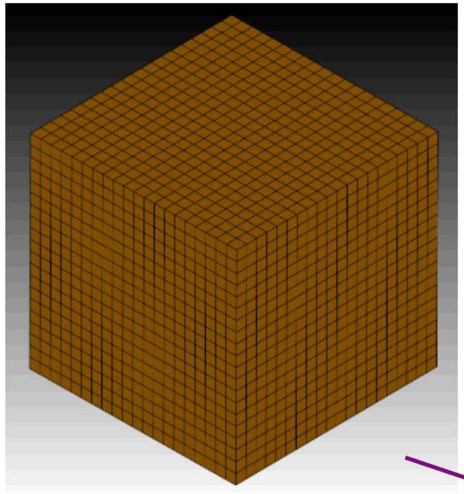
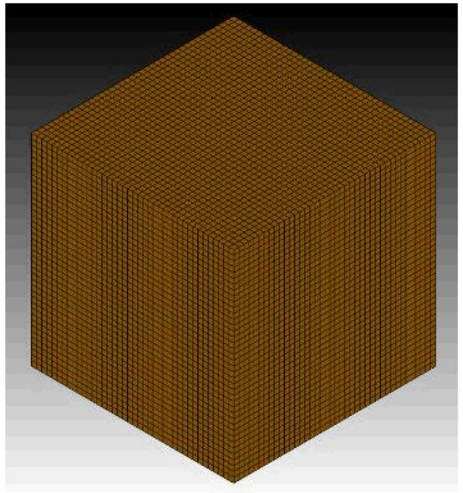
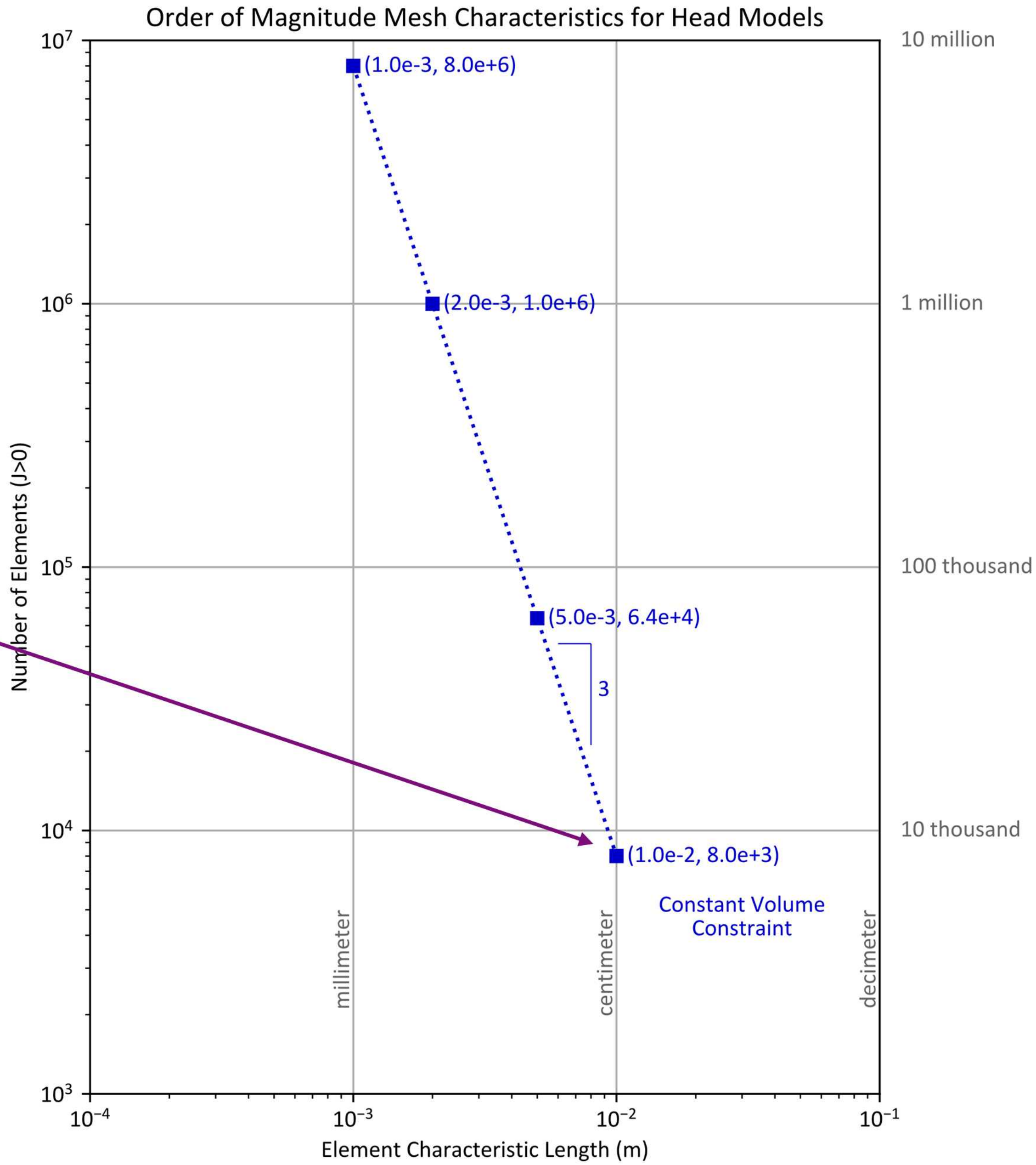
element length = 1 cm
8,000 elements



element length = 0.5 cm
64,000 elements





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Recent Models

(n=16)

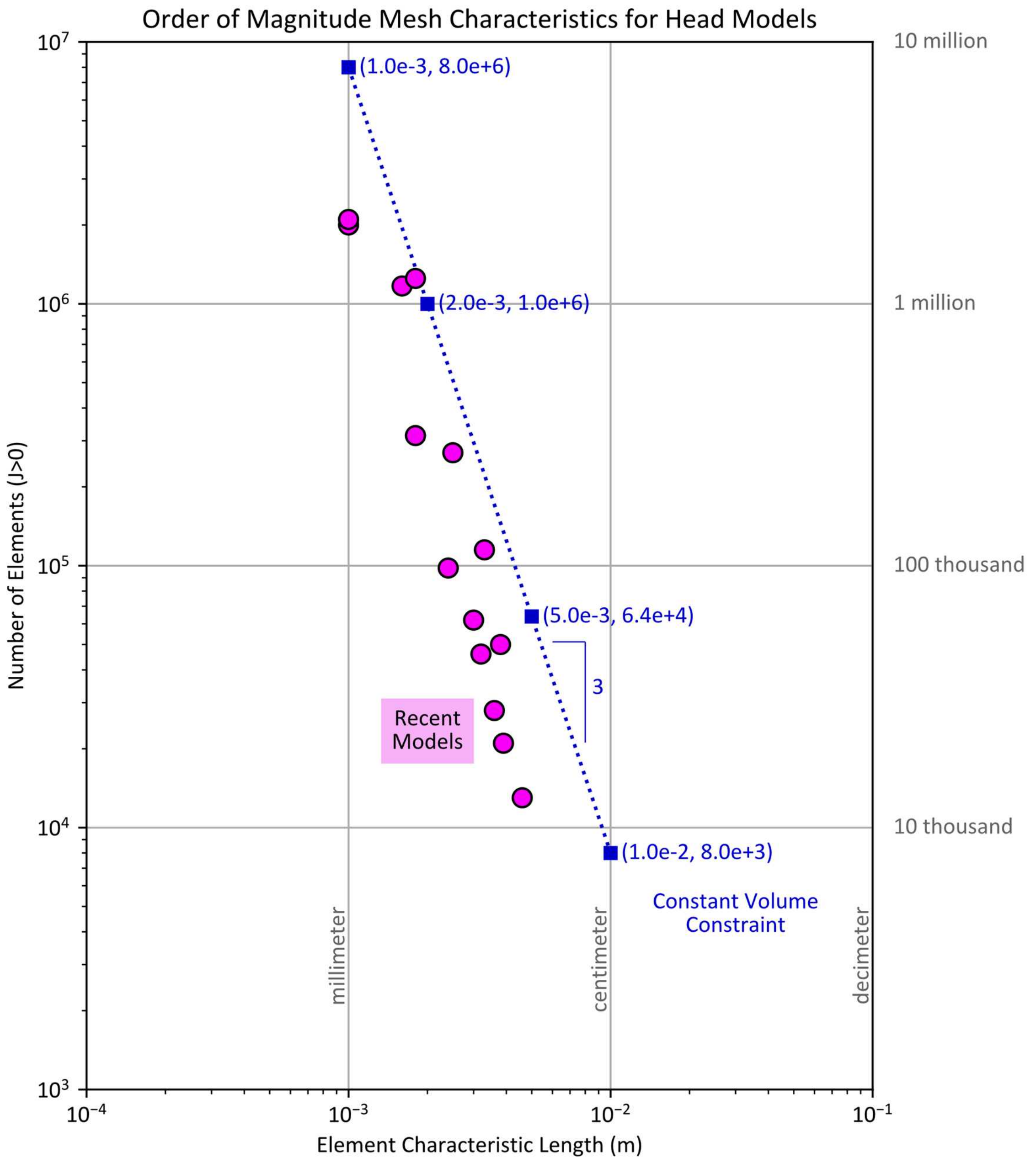
TABLE 1. Summary of numerical methods utilized in recent brain finite element models.

	WSUBIM	KTH	UCD	THUMS	SUFEHM	SIMon	KTH-Voxel	DSSM
Reference	Zhang *et al.*[92]	Kleiven and von Holst[58]	Horgan and Gilchrist[49]	Kimpara *et al.*[56]	Deck and Willinger[23]	Takhounts *et al.*[83]	Ho *et al.*[45]	McAllister *et al.*[64]
Nodes	282,000	17,000	–	38,000	12,000	43,000	–	102,000
Elements	314,000	21,000	28,000	50,000	13,000	46,000	2,000,000	98,000
Estimated mean resolution[g]	1.8 mm	3.9 mm	3.6 mm	3.8 mm	4.6 mm	3.2 mm	1.0 mm	2.4 mm
Element type	Hex. Quad.	Hex. Quad.	Hex. Quad.	Hex. Quad.	Hex. Quad.	Hex. Quad.	VoxS. Quad.	Hex. Quad.
Element formulation	–	Selectively Reduced	Constant Stress[f]	Constant Stress[f]	–	Constant Stress[f]	–	–
Gyrencephalic	No	No	No	No	No	No	Yes	No
Anisotropy	No	No[b]	No	No	No[c]	No	No	No
Viscoelasticity	Yes	No[a]	Yes	Yes	Yes	Yes	Yes	Yes
Hyperelasticity	No	Yes	No	No	Yes	No	Yes	Yes
Geometry	50th percentile male	Visible Human Database	Visible Human Database (Male)	50th percentile male	Human adult male	50th percentile male	–	Subject-specific (male)
Hourglass Control	–	–	–	Viscous	–	Viscous	–	–
Solver	PAM-CRASH	LS-DYNA	Abaqus	LS-DYNA	LS-DYNA	LS-DYNA	LS-DYNA	Abaqus

Model	GHBMC	Singapore	DHIM	WFUABM	Imperial college	JHU	Toyota	YEAHM
Reference	Mao *et al.*[62]	Yang *et al.*[89]	Ji *et al.*[52]	Miller *et al.*[65]	Ghajari *et al.*[37]	Ganpule *et al.*[31]	Atsumi *et al.*[3]	Fernandes *et al.*[25]
Nodes	101,000	293,000	101,000	2,000,000	–	–	42,000	–
Elements	270,000	1,170,000	115,000	2,100,000	1,250,000	–	62,000	–
Estimated mean resolution[g]	2.5 mm	1.6 mm	3.3 mm	1 mm	1.8 mm	2 mm	3.0 mm	–
Element type	Hex. Pent. Tet. Quad. Tri.	Tet. Tri.	Hex. Quad.	Vox. Quad.	VoxS. Quad.	Meshless	Hex. Quad.	Tet. Tri.
Element formulation	Constant Stress[f]	–	Constant Stress[f]	–	–	Material Point Method	–	Fully-integrated[e]
Gyrencephalic	No	Yes	No	Yes	Yes	Yes	No	Yes
Anisotropy	No	No	No[d]	No	No	Yes	Yes	No
Viscoelasticity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hyperelasticity	No	No	Yes	No	Yes	Yes	Yes	Yes

Reference: Giudice JS, Zeng W, Wu T, Alshareef A, Shedd DF, Panzer MB. An Analytical Review of the Numerical Methods used for Finite Element Modeling of Traumatic Brain Injury. Annals of biomedical engineering. 2018 Oct 30:1-8.

Recent Models
(n=16)



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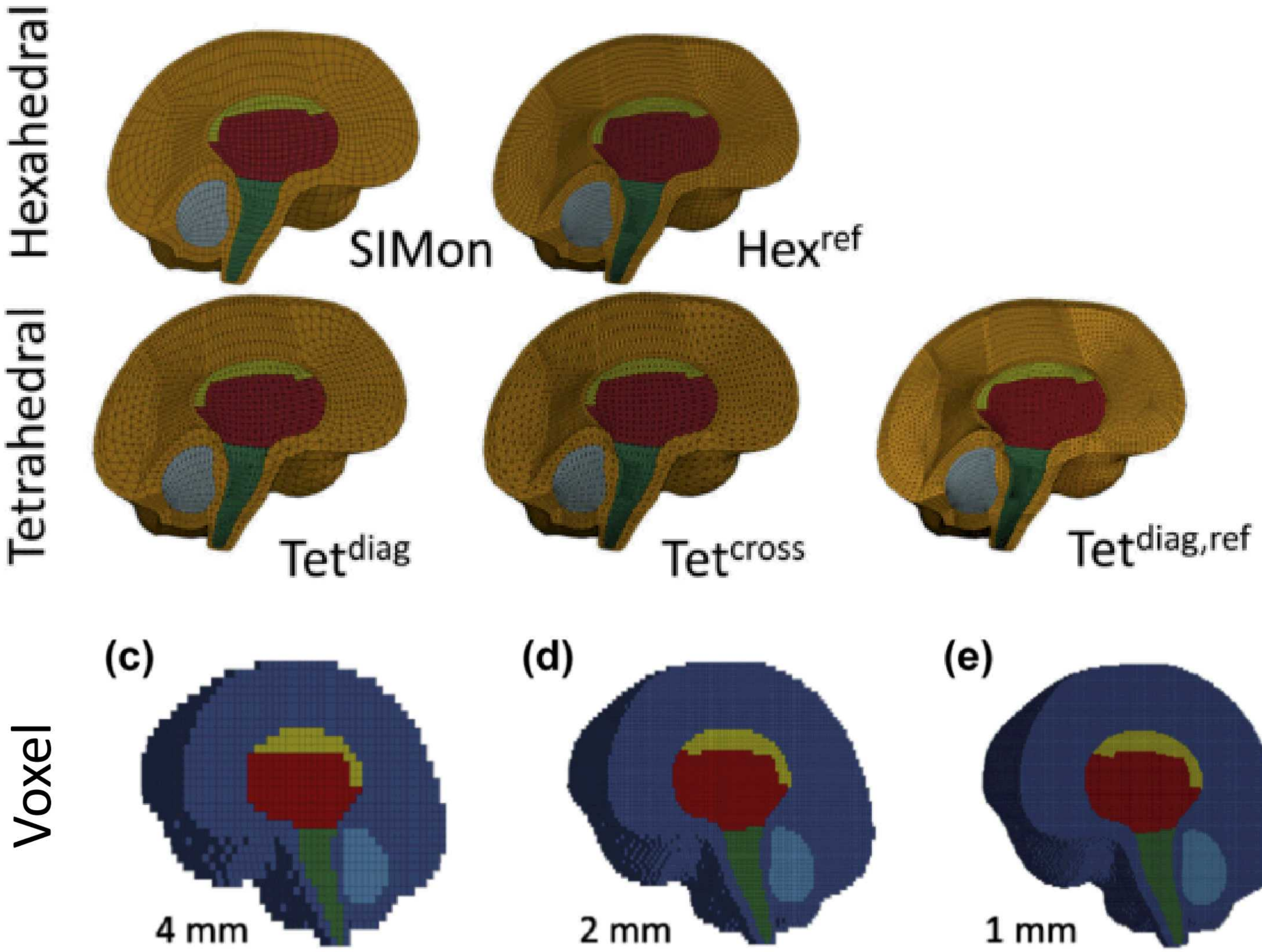
Giudice et al. 2018
Refinements



Mesh type	Number of elements	Mean characteristic length (mm)[a]
Baseline	45,877	2.07 ± 0.77
Hex^{ref}	345,244	1.07 ± 0.39
Tet^{diag}	250,484	1.69 ± 0.66
Tet^{cross}	990,860	0.99 ± 0.37
$Tet^{diag,\ ref}$	1,984,051	0.84 ± 0.33
$Vox^{4\ mm}$	30,228	4.0
$Vox^{2\ mm}$	207,514	2.0
$Vox^{1\ mm}$	1,526,114	1.0

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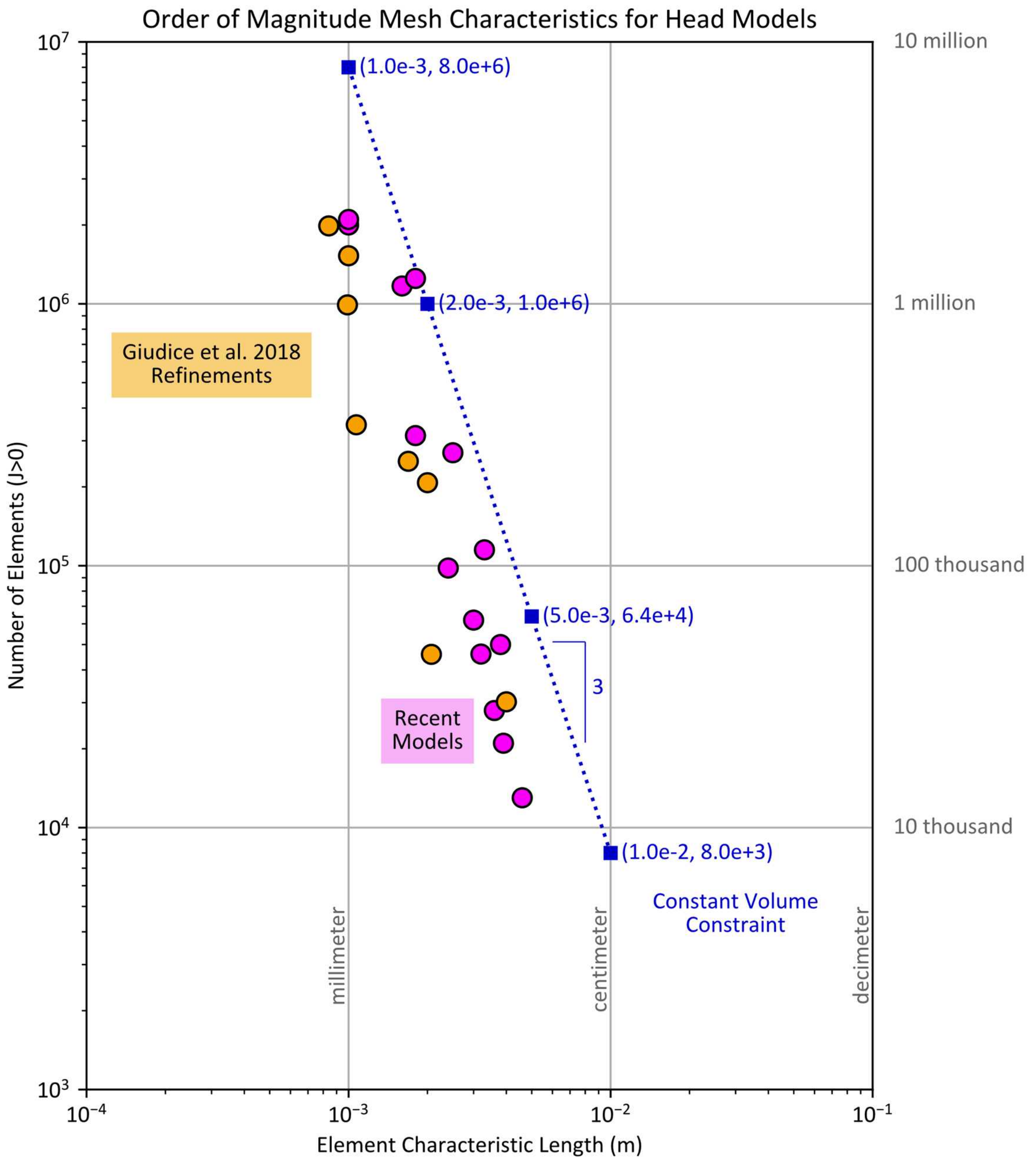
Reference: Giudice JS, Zeng W, Wu T, Alshareef A, Shedd DF, Panzer MB. An Analytical Review of the Numerical Methods used for Finite Element Modeling of Traumatic Brain Injury. Annals of biomedical engineering. 2018 Oct 30:1-8.

Giudice et al. 2018 Refinements



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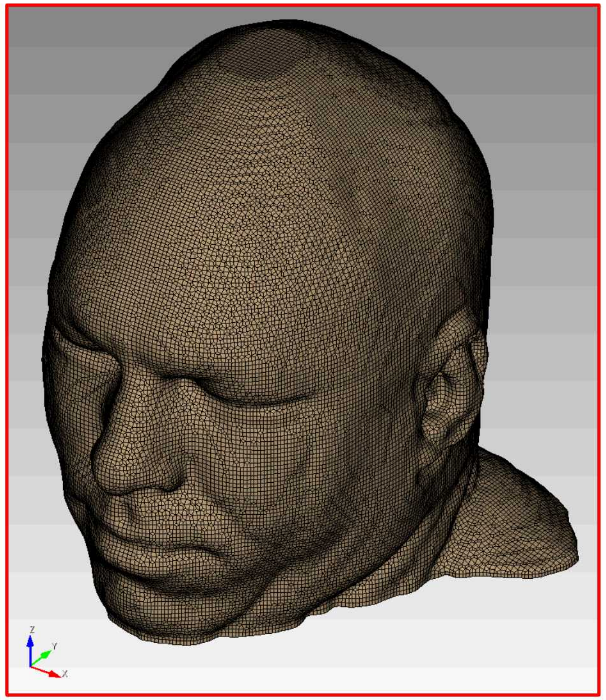

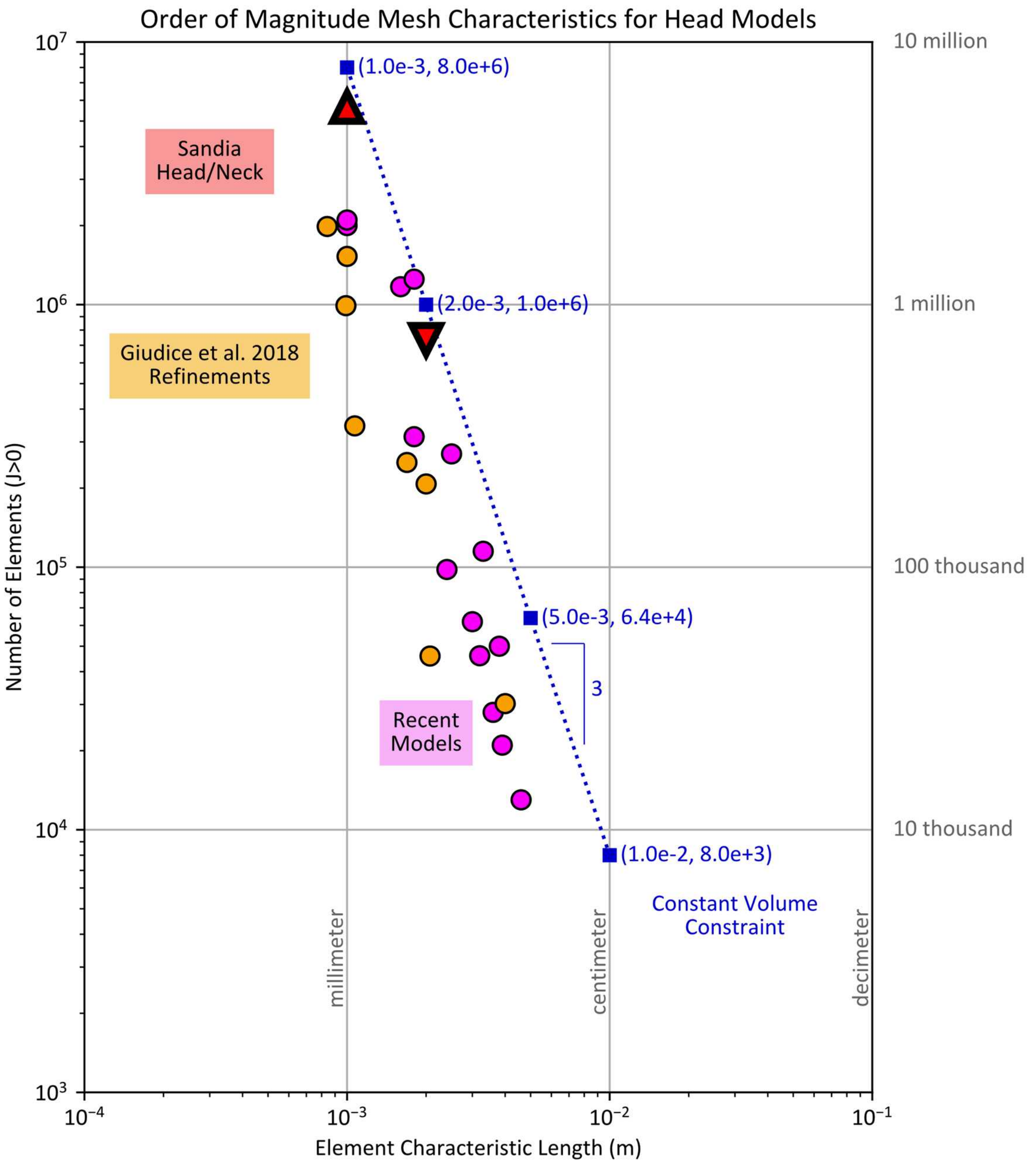

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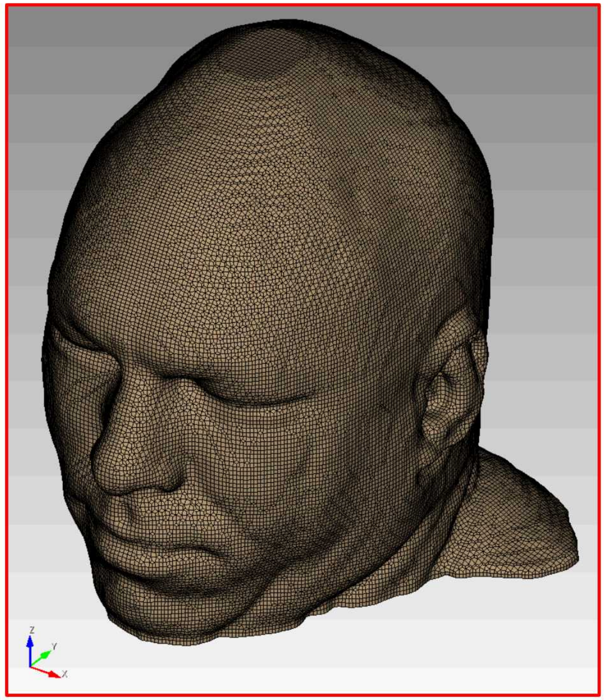

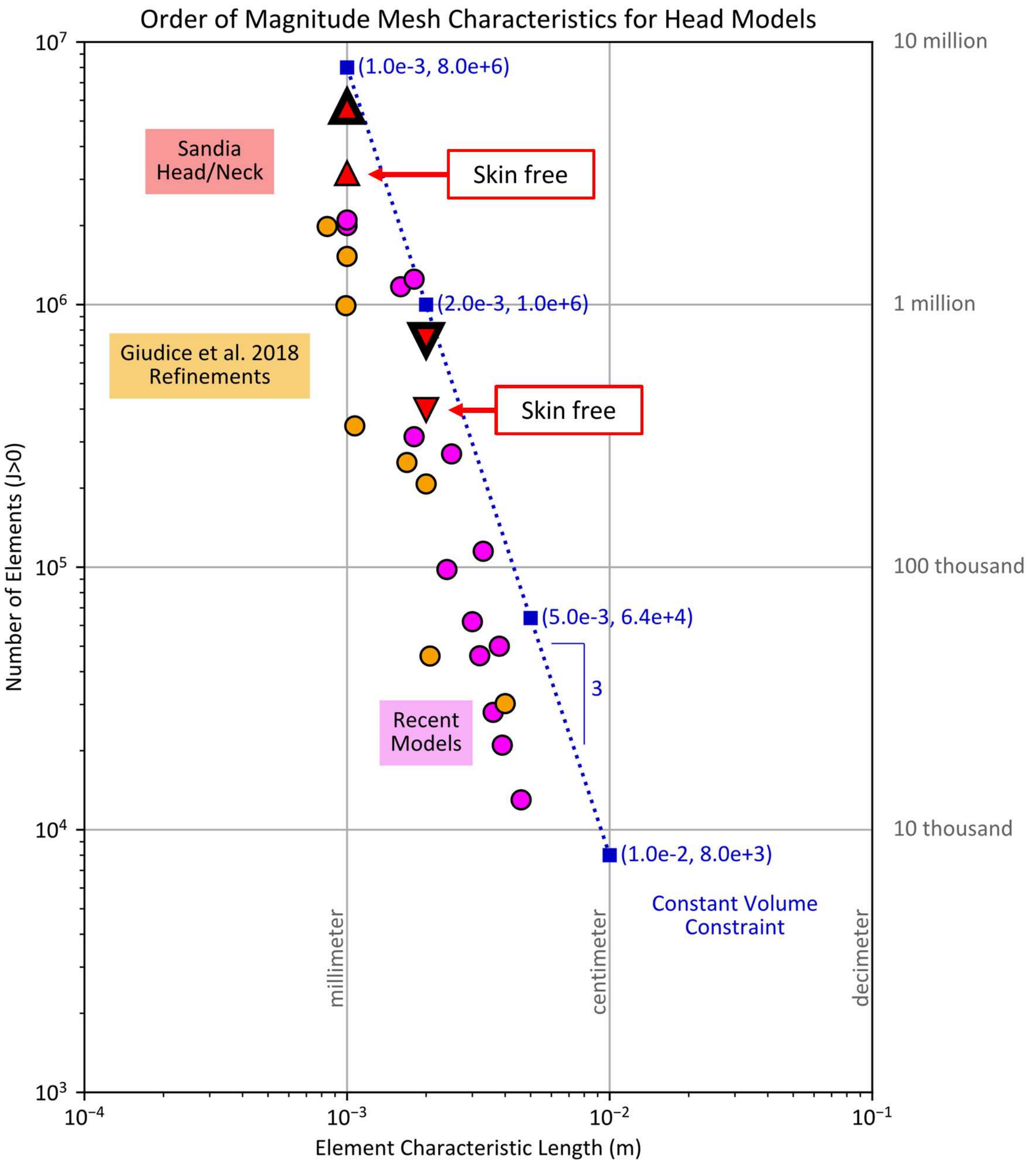

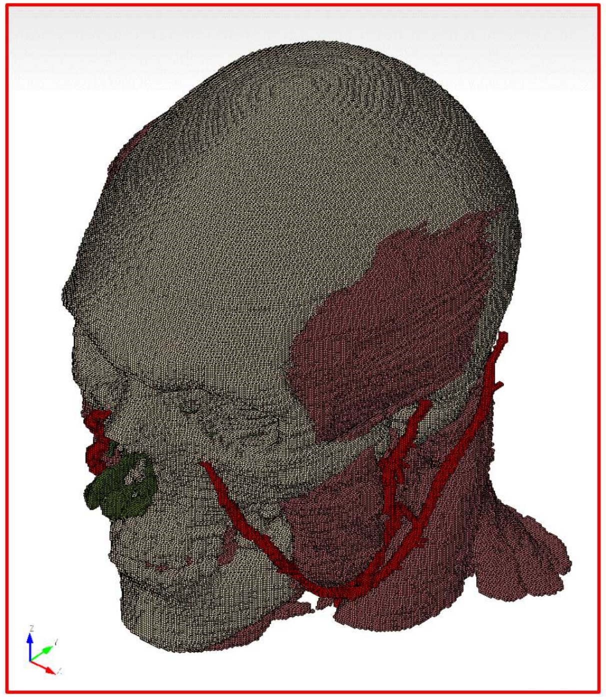

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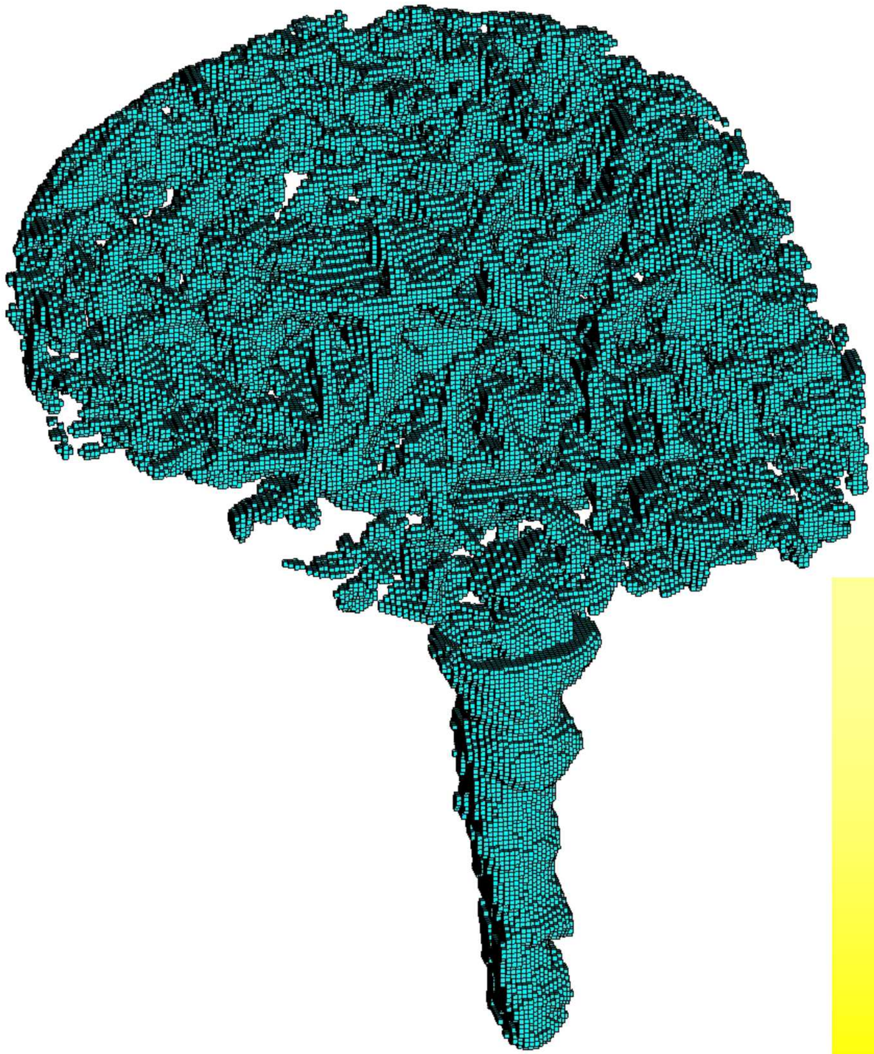
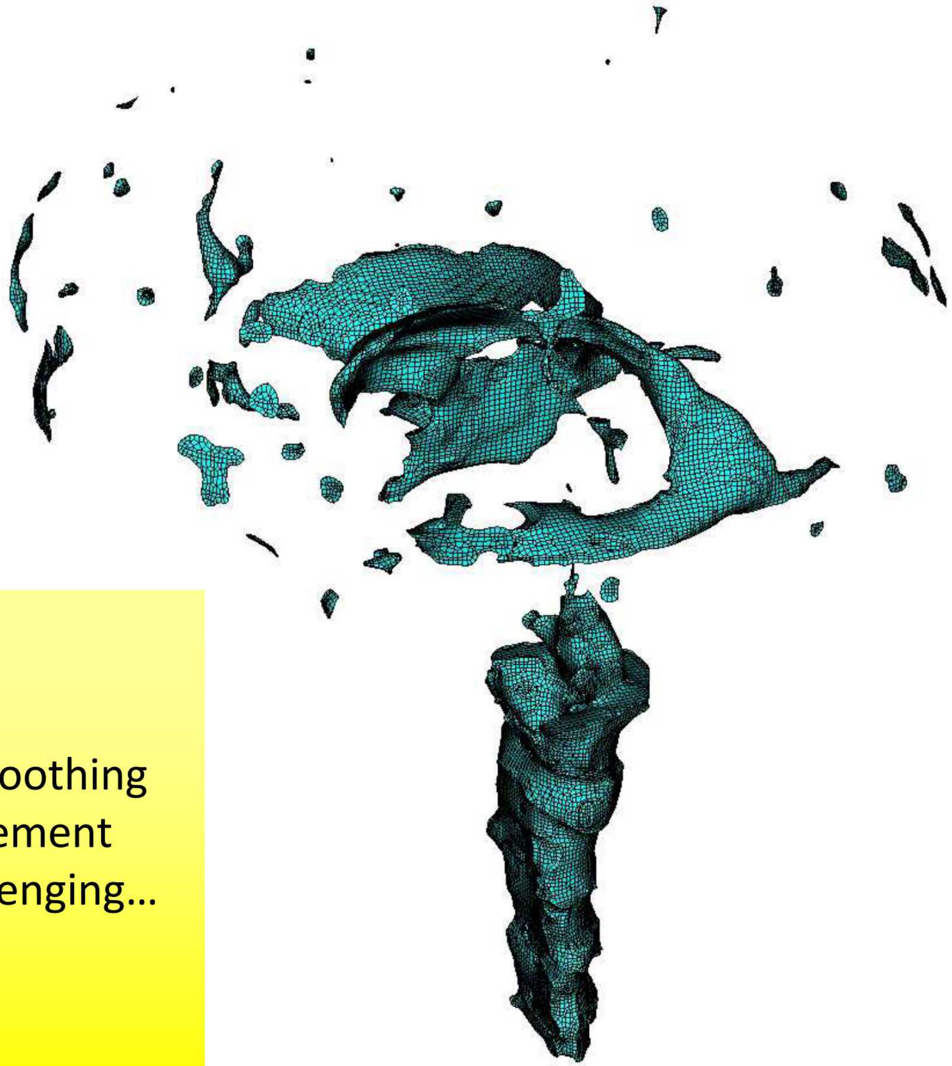
Voxel mesh

CSF Layer

Defeatured and Smoothed





Internal smoothing and refinement can be challenging…

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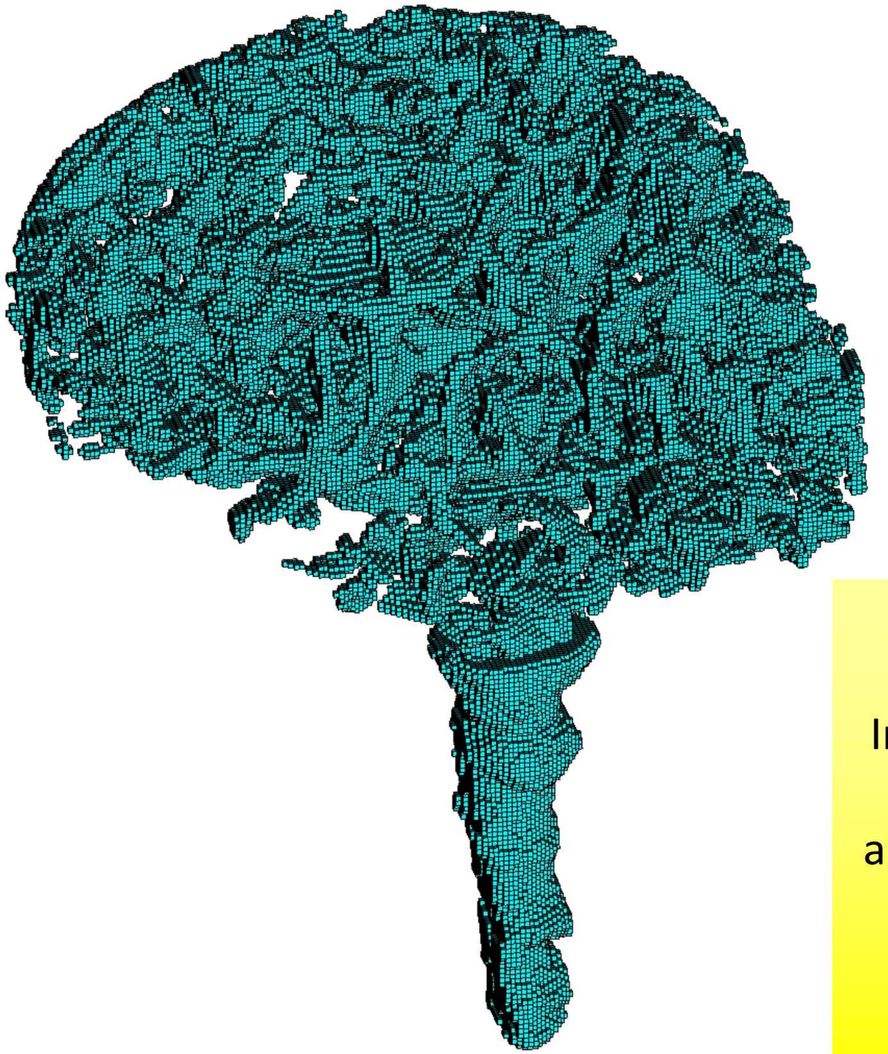
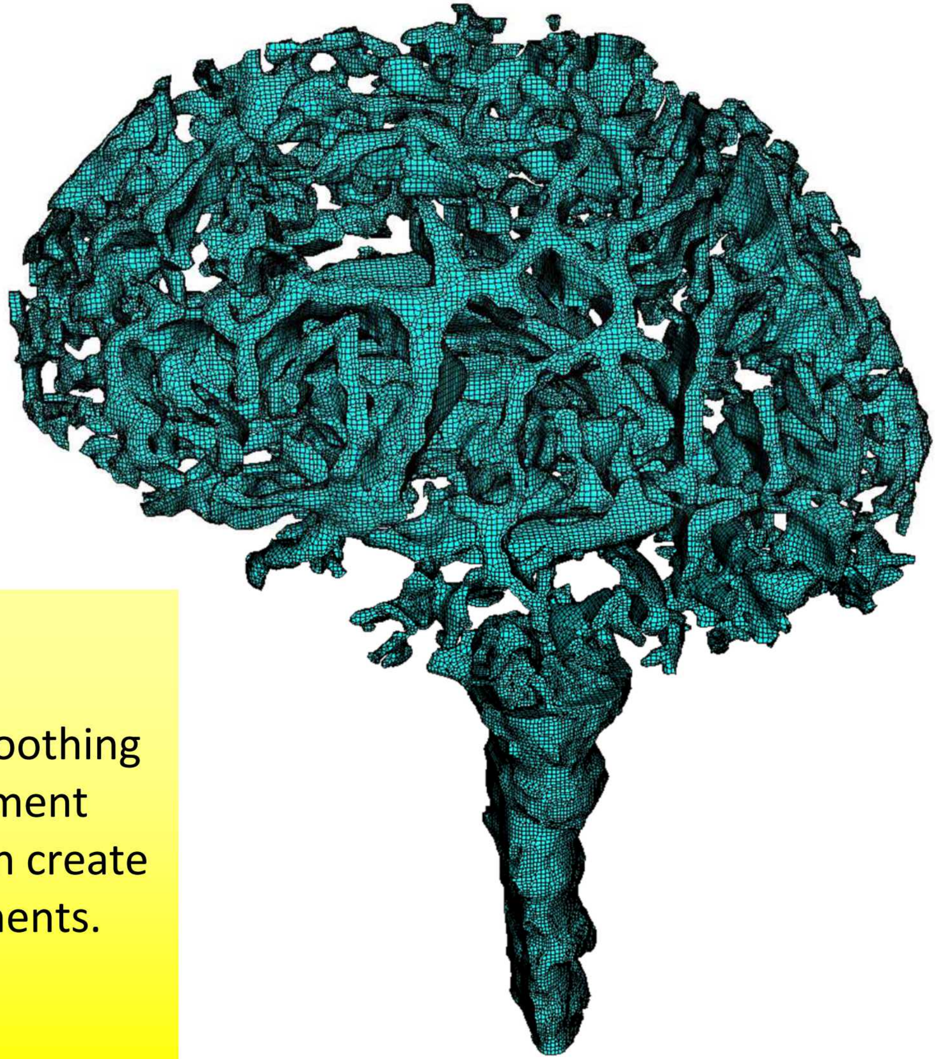
Voxel mesh | CSF Layer | Defeatured and Smoothed





Improved smoothing and refinement algorithms can create > 10M elements.

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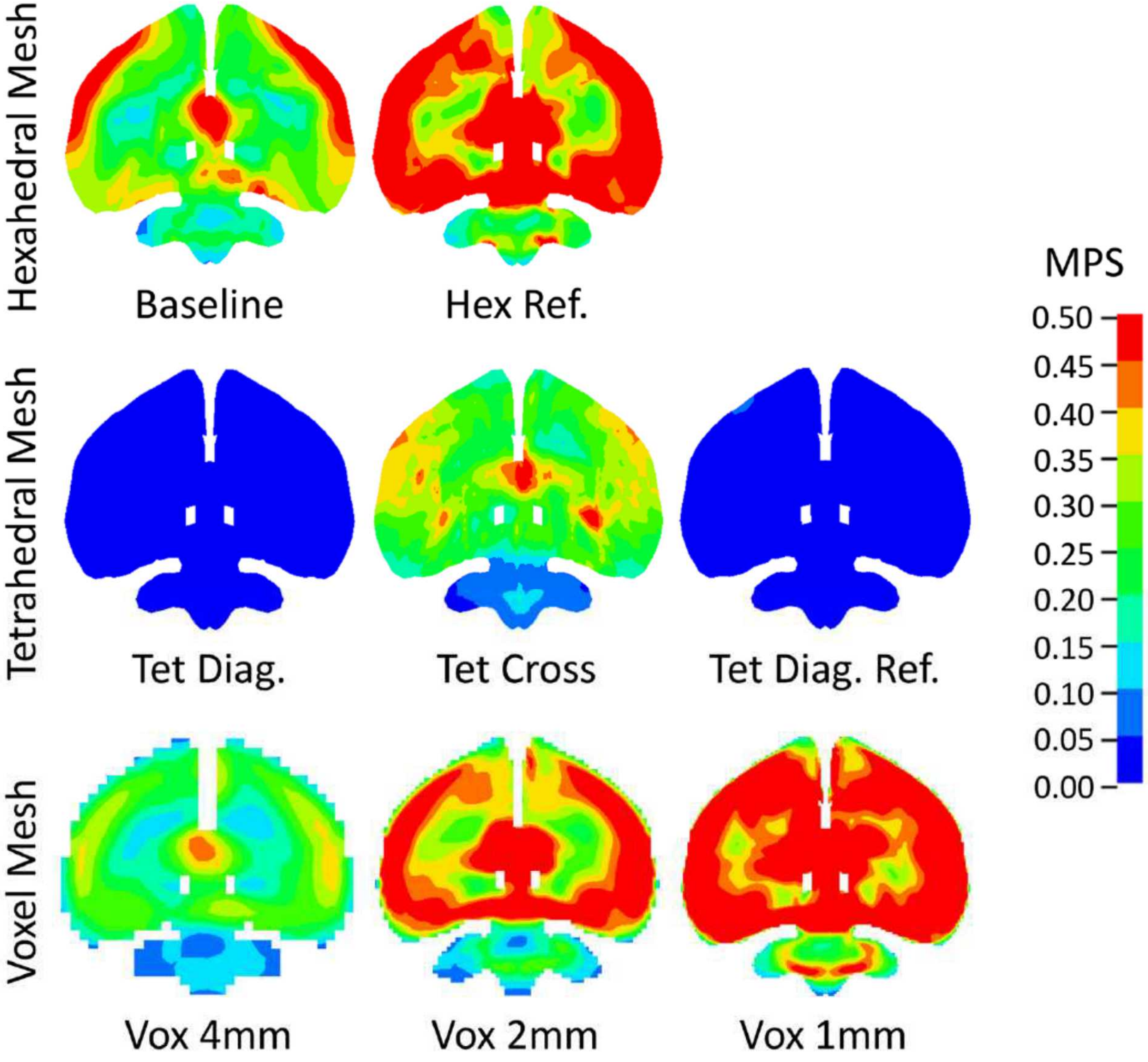


FIGURE 6. Maximum principal strain (MPS) distributions for the simulations run to investigate the effect of mesh type and refinement. As each of the hexahedral and voxel meshes were refined, an increase in brain deformation was observed. These results suggest that the brain model response, at these levels of mesh refinement, is not converged to a mesh-independent solution and is influenced by mesh size and element type. MPS contours are mapped to the undeformed mesh.

Sufficient element density (and type) is necessary for convergence.

Reference: Giudice JS, Zeng W, Wu T, Alshareef A, Shedd DF, Panzer MB. An Analytical Review of the Numerical Methods used for Finite Element Modeling of Traumatic Brain Injury. Annals of biomedical engineering. 2018 Oct 30:1-8.

Summary

Head/neck/torso high-fidelity human models

- high-fidelity: 6M elements, 1-mm resolution
- finite volume and finite element
- blast, blunt, and ballistics

Please see www.sandia.gov/biomechanics for

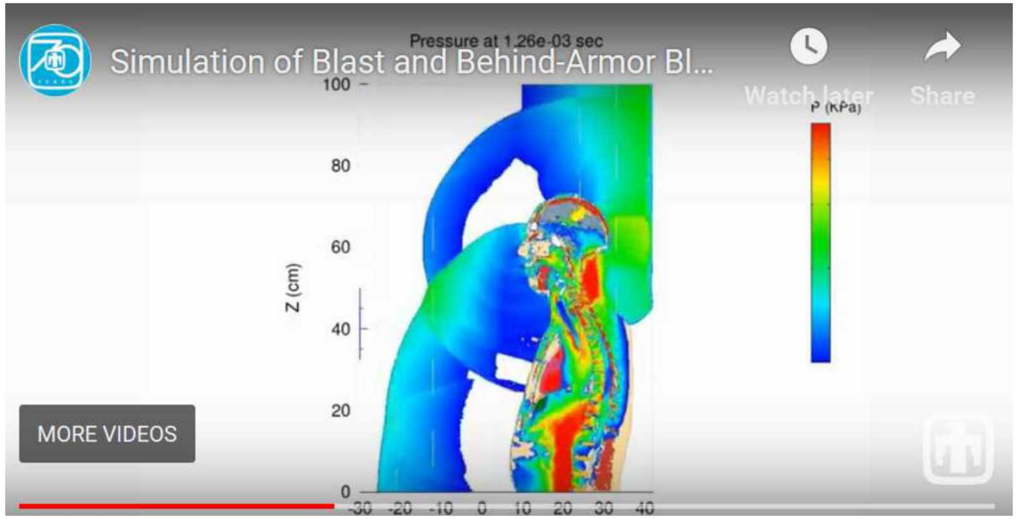
- simulation videos
- UUR publications, SAND Reports

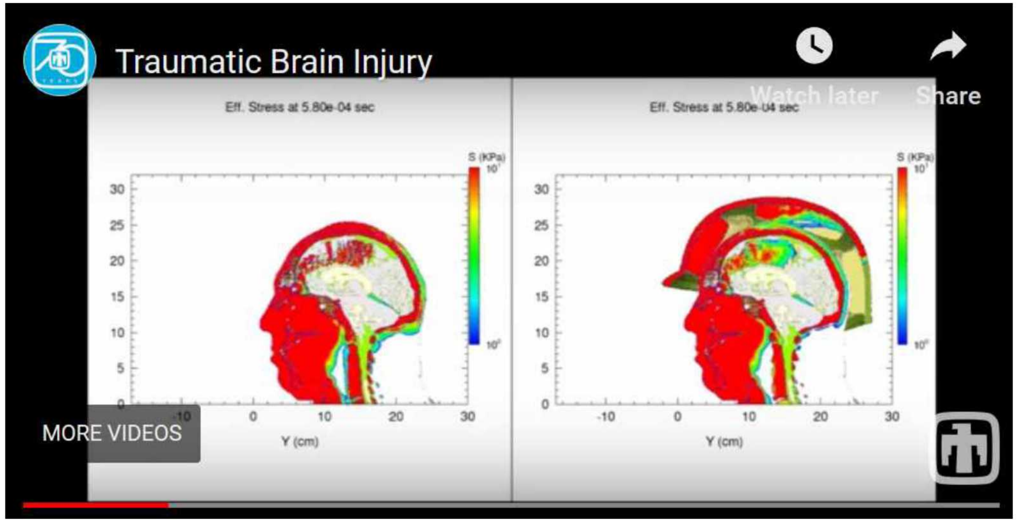
Competing Issues

- sufficiently small resolution (1-mm or <)
- sufficiently dense (1M elements or >)
- sufficient for convergence?

Acknowledgements

- Sandia Laboratory Directed Research & Development (LDRD)
- Office of Naval Research (ONR)





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Thank you.

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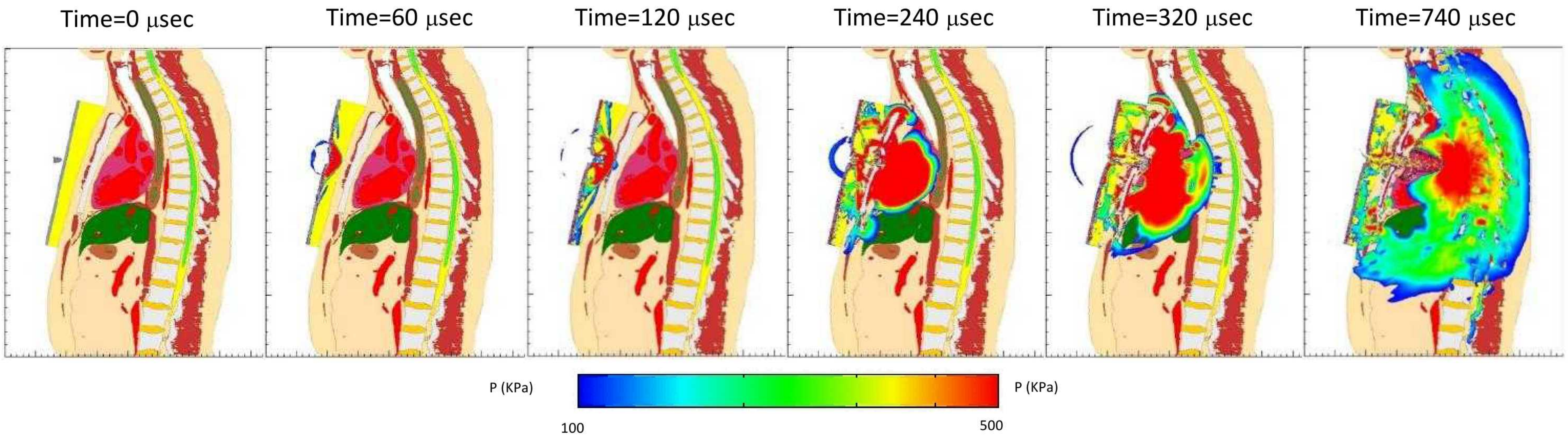

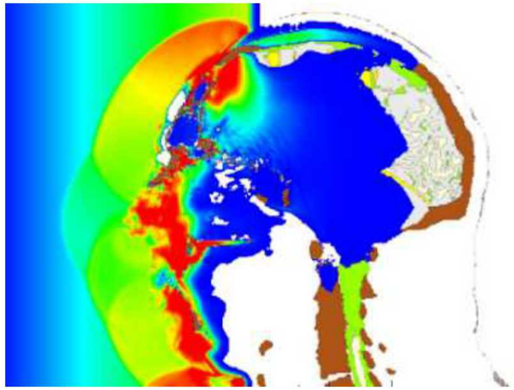

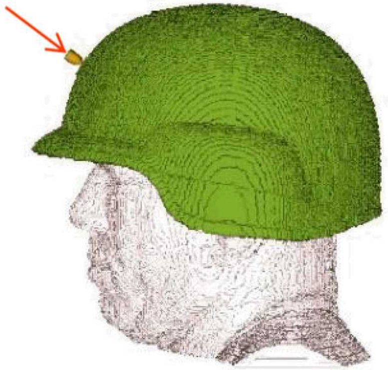

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