Development of Hybrid Newborn Computational Phantom for Dosimetry Calculation: The Skeleton

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Presentation Outline

- Introduction
  - Basic skeletal anatomy
  - Skeletal dosimetry applications
  - Evolution of phantoms
  - History and limitations of current dosimetry models

- Methods and Materials
  - Construction of UF homogeneous hybrid newborn NURBS skeleton
  - Construction of UF heterogeneous hybrid newborn NURBS skeleton
  - Electron dosimetry modeling for UF NURBS newborn skeleton

- Results and Discussion
  - Tissue data for UF newborn hybrid NURBS skeletal model
  - Absorbed fraction data

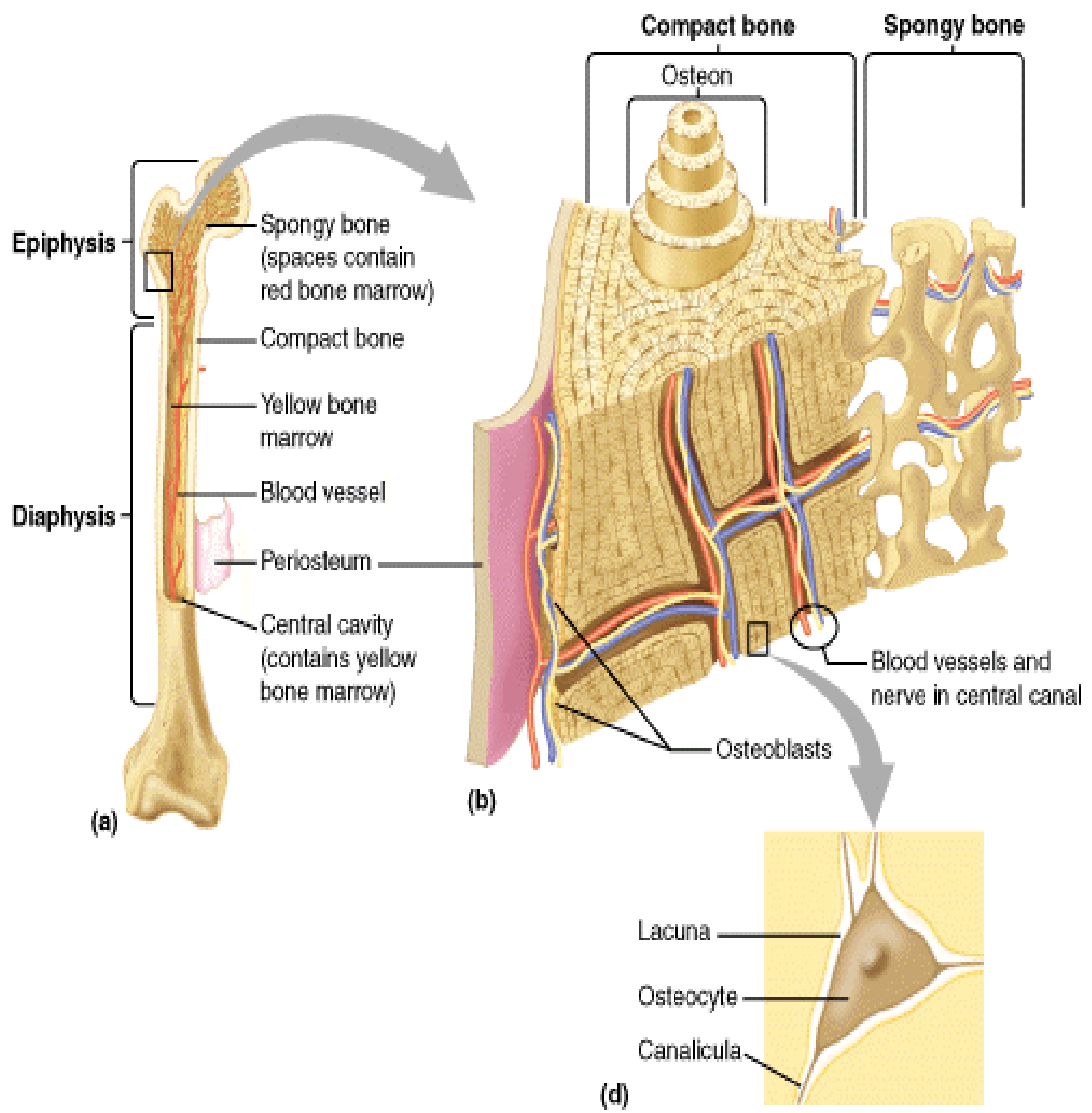
- Conclusions and Future Work

Introduction

General Features of Bone

Skeletal Structure:

- 2 Types of Bone:
  - Cortical bone
  - Trabecular bone
- Cortical (compact) bone
  - Periosteum
  - Osteon
  - Haversian/Volksmann Canals
- Trabecular ("spongy") bone
  - Network of irregular, interlacing bone along lines of stress
  - Cavities with active ("red") marrow and inactive ("yellow") marrow
  - 50 - 4000μm marrow cavities
  - Age/skeletal site-specific; intersubject variability

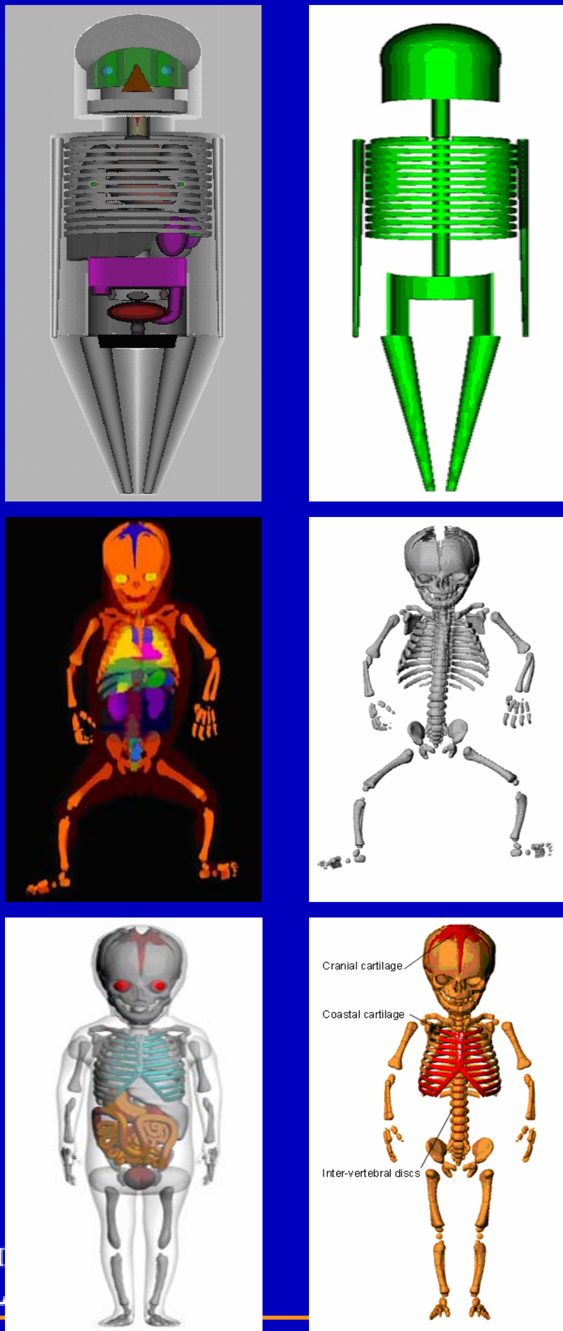


Skeletal Dosimetry Applications

- Radiation protection/epidemiological risk assessments
  - Techa River contamination (about 30,000 people exposed)
    - Mayak Production Association in Southern Urals of Russia (1949-1956)
    - Waste management failures and radioactive waste storage facility explosion
    - 10^{17} Bq (~27 MCi) liquid waste (Sr, Cs, Y, Ba, La, I)
    - US – Russian JCCRER (Joint Coordinating Committee on Radiation Effects Research)
  - Chernobyl accident (~5 million living in contaminated areas at time of release)
    - Ukraine (1986)
    - I-131 and Cs-137 (10^{18} Bq → about half biologically inert noble gases)
    - Increase in thyroid cancer in children
  - Leukemia risks from multiple CT exams and IVF

- Medical applications (bone marrow is dose-limiting organ – marrow toxicity)
  - Radioimmunotherapy (RIT)
    - Tag tissue-specific antibody to beta-particle emitting radionuclide
    - Cancers outside hematopoietic system (e.g. osteosarcomas, liver cancer, tumor growths)
  - Radiotherapy
    - Bone marrow ablation using external beam or bone-seeking radiopharmaceuticals
    - Localization of radiation within hematopoietic system
    - Hodgkin’s or non-Hodgkin’s lymphoma; leukemia

Evolution of Computational Phantoms



- Stylized phantom
  - Advantage: Organ repositioning and shape deformation
  - Disadvantage: Anatomically unrealistic
- Voxel-based phantom
  - Advantage: Anatomically more realistic, image-based
  - Disadvantage: Limited organ transformation to match an individual
- NURBS (Non-uniform rational B-spline) phantom
  - Hybrid of advantages of stylized and voxel-based models
    - Flexibility of organ transformations
    - Image-based, realistic anatomy

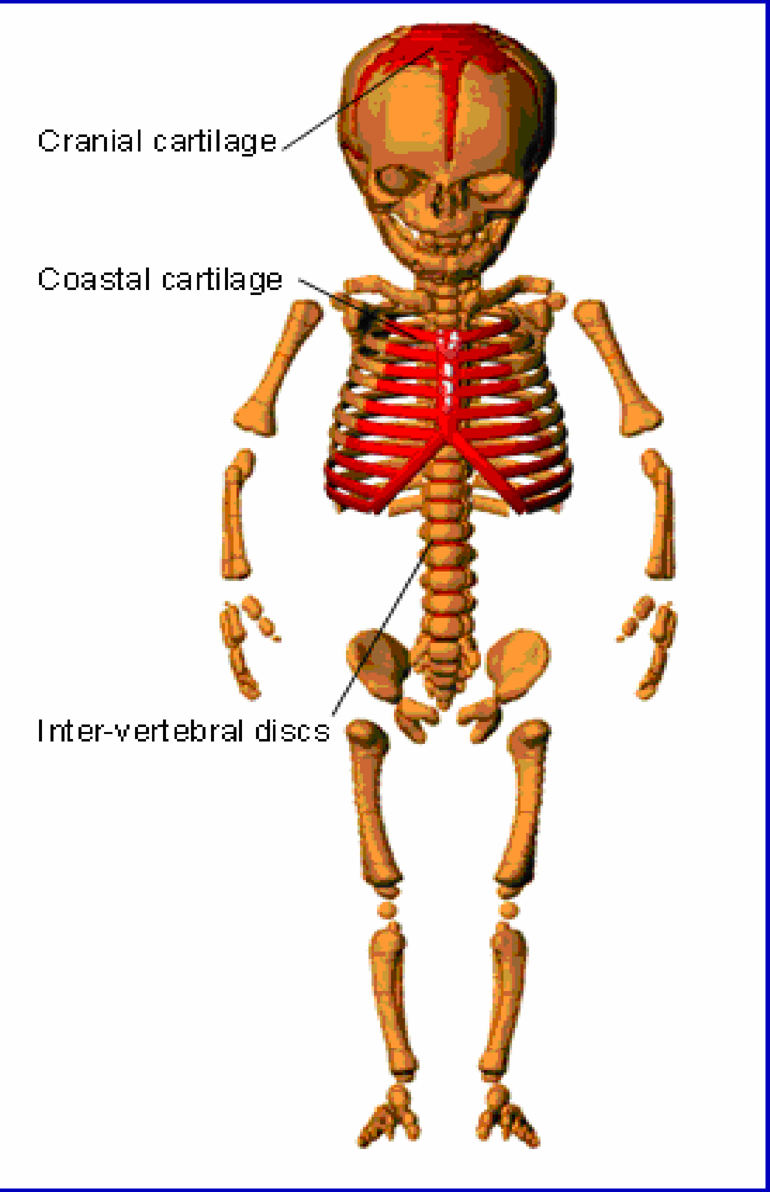
Historical Approach to Skeletal Dosimetry

- Historic perspective
  - 50+ years of skeletal dosimetry research
    - FW Spiers and colleagues at the University of Leeds
      - » 1949 - 1981
      - » Development of chord distributions used today
    - Keith Eckerman and Michael Stabin at ORNL
      - » 1980s to present
      - » Development of current stylized (mathematical) Reference Man model
      - » Development of ICRP pediatric age series models (currently used in clinic – OLINDA and MIRDOSE)
    - UF Bone Imaging and Dosimetry (BID) Group (late 1990s to now)
      - » Development of 'image-based' voxel adult male and adult female skeletal models
      - » Development of first 'image-based' pediatric combination whole body (POD group) and skeleton (this presentation) computational phantoms

Limitations of Current Pediatric Electron Skeletal Dosimetry Models: (Eckerman and Stabin HP 2000, Stabin and Siegel HP 2003)

- **Transports through an infinite medium**
  - **Does not account for particle escape from microstructure**
- **Accounts for cellularity after transport and not during transport**
  - **Only valid at high electron energies (greater than 1 MeV)**
  - **Bolch et al. (J Nucl Med – 2002)**
- **10 micron endosteal layer model for osteoprogenitor cell population**
  - **Recommended extension to 50 microns**
  - **Gossner et al. (Radiation Protection Dosimetry – 2000, 2003)**
- **Skeletal masses are tied to stylized (mathematical) models**
  - **Anatomically unrealistic**
- **Skeletal-averaged absorbed fraction data**
  - **Significant changes in shape, size, and trabecular microstructure**
  - **Beddoe et al. (Phys. Med. Biol. – 1976), Kneissel et al. (Calcif Tissue Int – 1997), Glorieux et al. (Bone – 2000), Byers et al. (Bone – 2000), Roschger et al. (J of Structural Biology – 2001)**

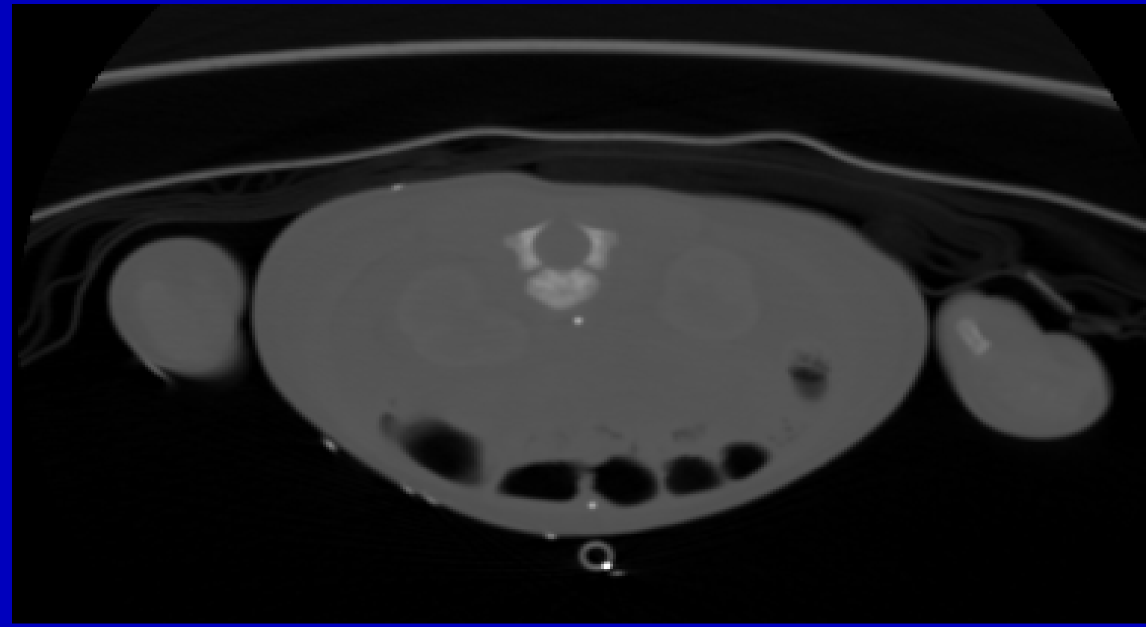
Research Design and Methods

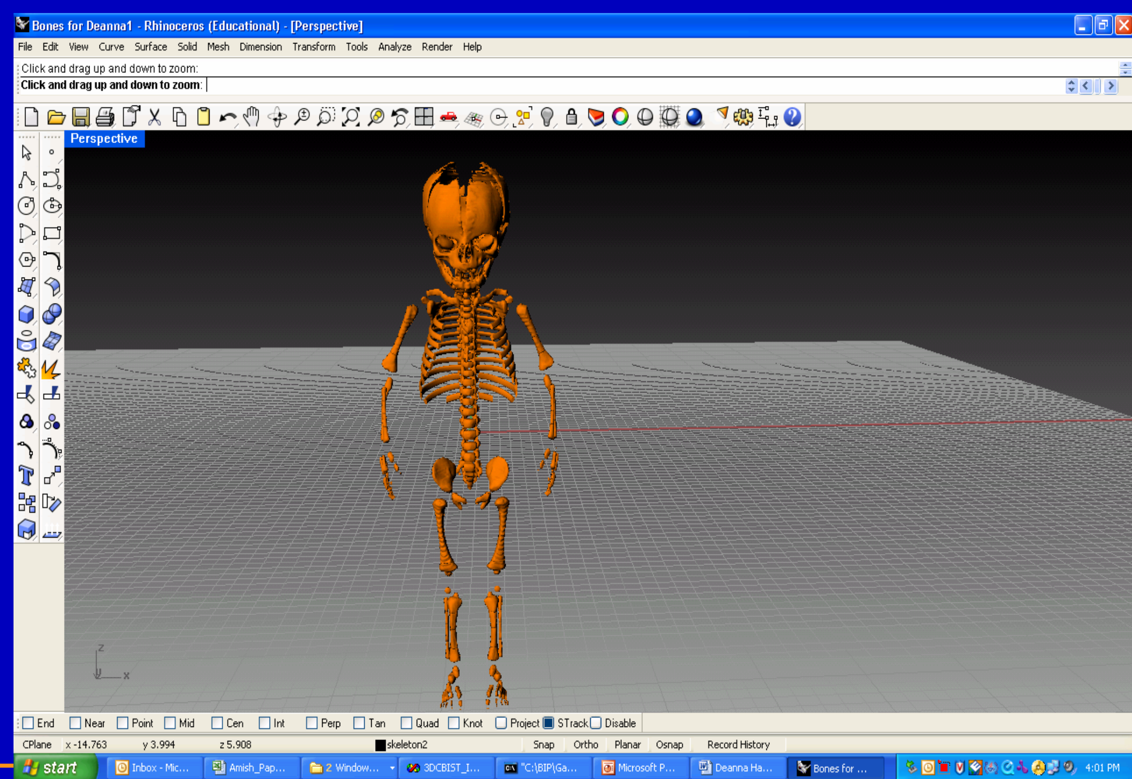


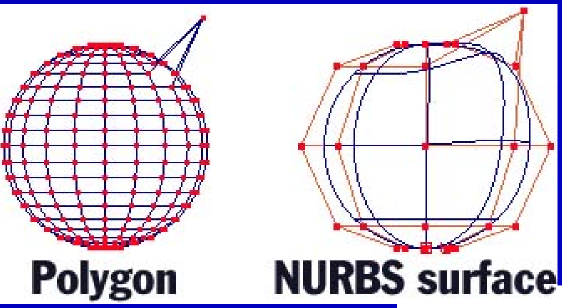
Construction of UF NURBS Homogeneous Newborn Skeleton

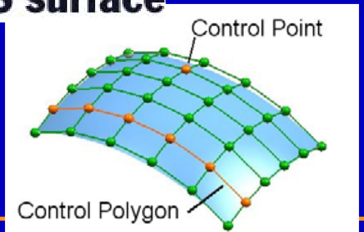
– **Segment in-vivo CT scans of ICRP ages using 3D-DOCTOR**
  - **1 mm slice thickness**
  - **Cartilage and homogeneous (spongiosa + cortical)**

– **Import into Rhinoceros for polygon mesh/NURBS modeling**









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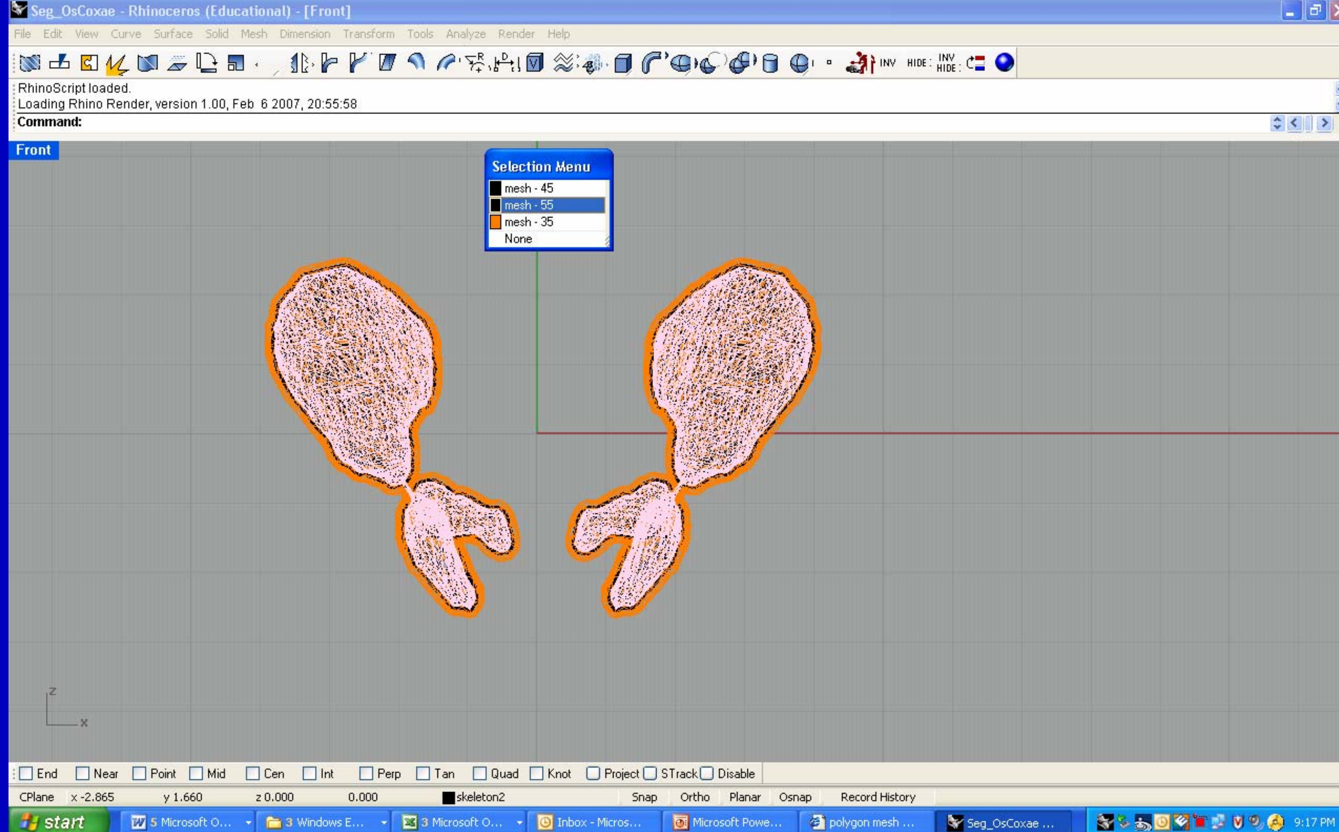

Construction of UF NURBS Heterogeneous Newborn Skeleton

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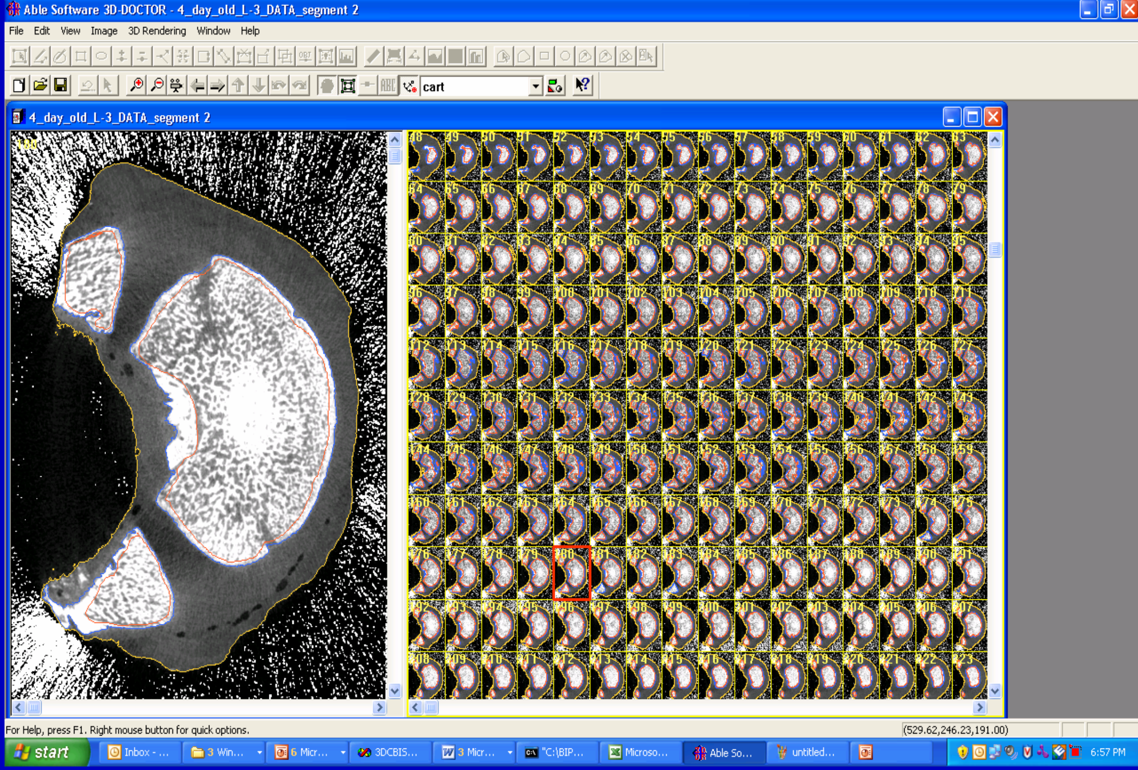
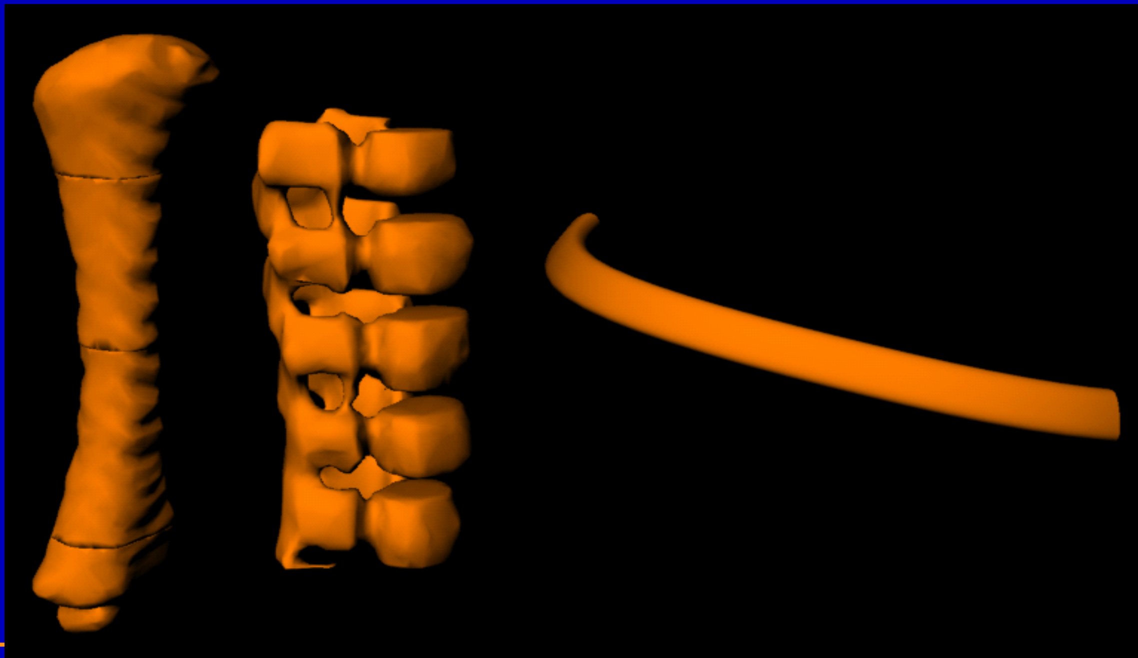
Gator Engineering

- Segment microCT scans from autopsy specimens using 3D-Doctor
  - Shands/SETA
  - Cartilage, spongiosa, and cortical bone boundaries
  - CBVF, SVF, CVF



- Extract individual bone sites from homogeneous skeleton model



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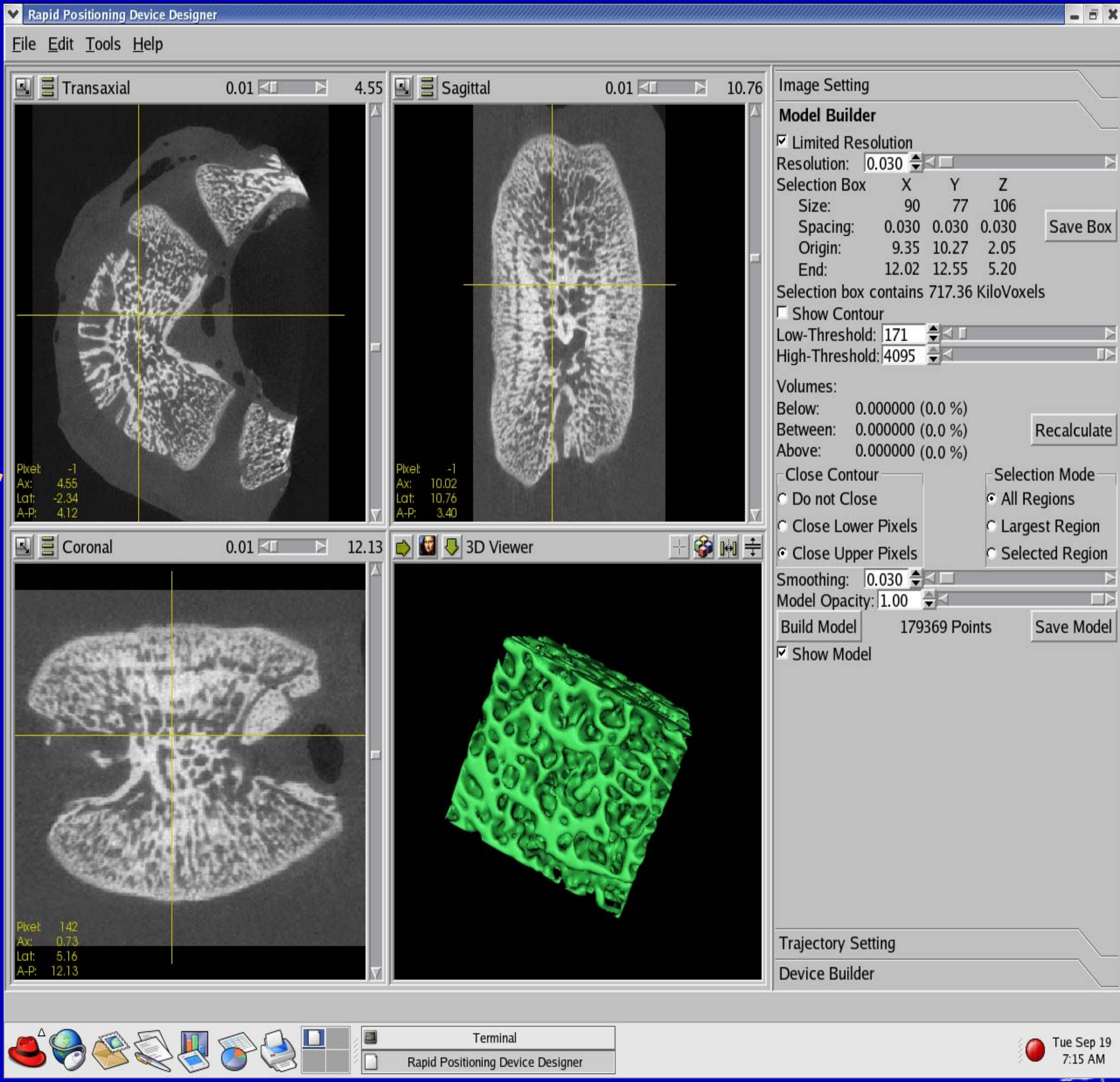
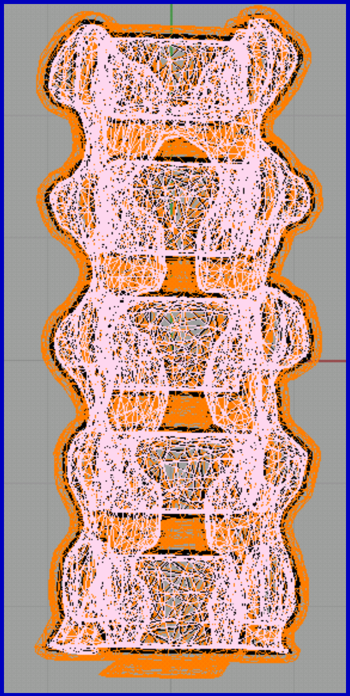
– microCT samples at 30 microns (SCANCO – Switzerland)

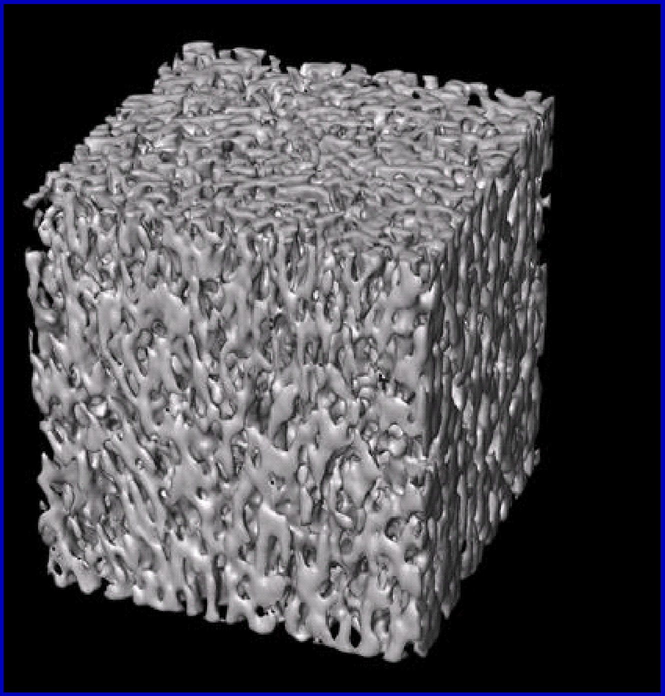
– Select threshold value to auto-segment trabecular bone and marrow (Rajon *et al* 2006)

  • MVF, BVF

– Couple micro- and macro-images for EGSnrc electron simulations



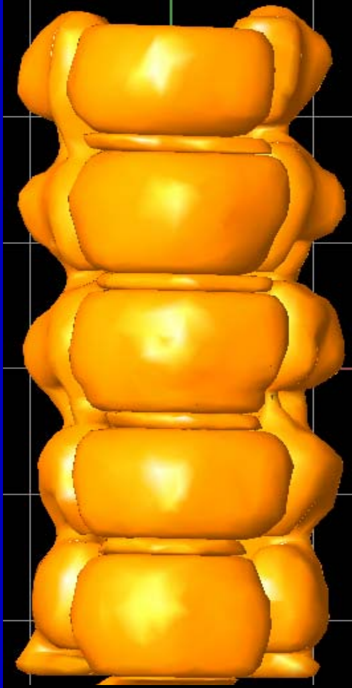


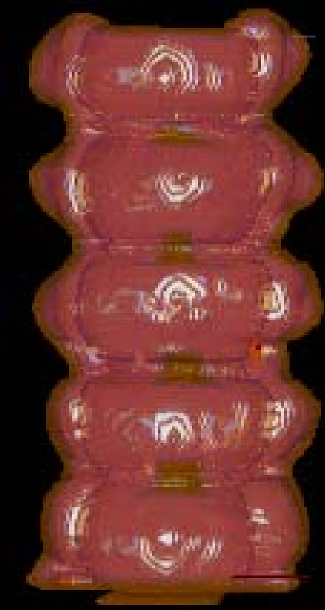


Electron Dosimetry Modeling for Newborn NURBS/Polygon Mesh Skeleton Model

Voxelizer (Lee et al. 2007 PMB)

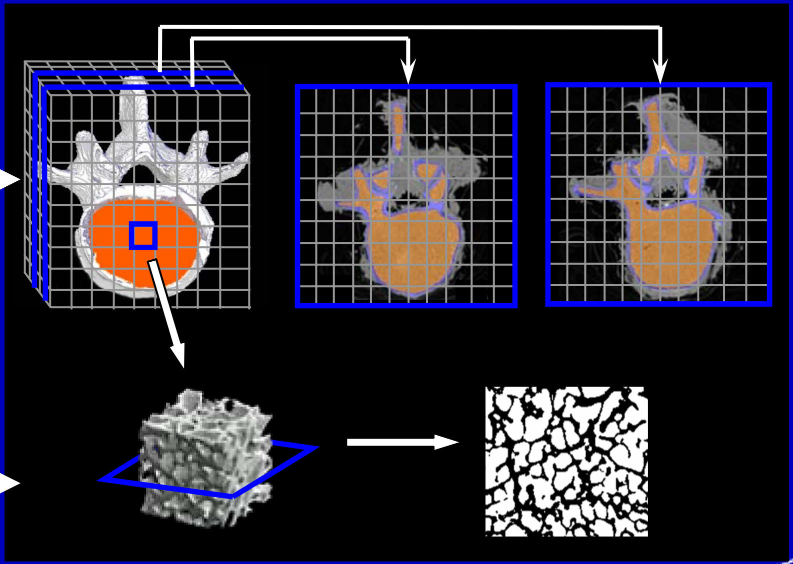
- **Need to voxelize polygon mesh/NURBS**
- **Macrostructure voxelized between 50 µm^3 and 200 µm^3 (bone site-dependent)**
- **Lumbar spine**
  - **50 µm^3 voxel resolution (~6 hours)**
  - **470 x 512 x 1096 voxels**
  - **~260 MB binary file**
  - **Convert to '.con' file (tag values; compresses file; ~3 MB)**
  - **Reasonably match mathematically derived tissue volumes (Hasenauer *et al*. to be submitted PMB)**
    - ***Cortical Bone Volume (within 10%)***
    - ***Cartilage Volume (less than 1%)***
    - ***Spongiosa Volume (less than 1%)***





Paired-Imaged Radiation Transport (PIRT)

- Amish Shah, 2004
- 66-Y male complete skeletal voxel model
- EGSnrc
- Simultaneous electron transport simulation within:
  - Polygon mesh/NURBS (cortical bone, soft tissue, spongiosa, and cartilage)
    - CT imaging; 3D contour of true skeletal structure
  - Microstructure (TAM_{50}, TAM, TIM, TBV, TBS)
    - microCT imaging; 3D image of skeletal spongiosa
    - 4 Day/5 Day
    - 30 μm^3
      - ~ 150 x 250 x 100 voxels
      - ~ 3.75 MB

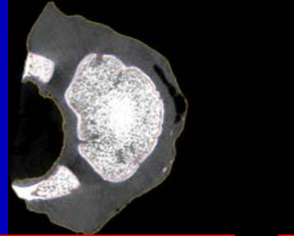


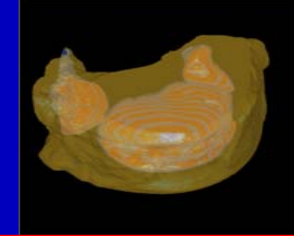
Results and Discussion

Skeletal Site	Polygon Mesh/NURBS Volumes: Cortical Bone + Spongiosa (cm³)	Polygon Mesh/NURBS Volumes: Cartilage Bone-Associated (cm³)	Polygon Mesh/NURBS Volumes: Total Homogeneous Bone (cm³)	Voxel Volumes: Cortical Bone + Spongiosa (cm³)	Voxel Volumes: Cartilage Bone-Associated (cm³)	Voxel Volumes: Total Homogeneous Bone (cm³)
[1]Cranium	57.71	35.90	103.01	57.78	35.66	102.91
Mandible	4.65	2.46	7.11	4.65	2.45	7.09
[1]Cervical	6.51	3.99	10.69	6.48	3.86	10.51
[1]Thoracic	11.18	7.46	19.25	11.22	7.27	19.08
[1]Lumbar	6.43	3.93	10.78	6.42	3.89	10.73
Sternum	0.51	1.46	1.97	0.51	1.47	1.98
[1,2]Ribs	18.30	4.11	33.01	18.13	4.08	32.74
Scapulae	4.23	2.47	6.71	4.23	2.48	6.71
Clavicles	1.57	1.20	2.78	1.57	1.22	2.79
Os coxae	9.17	5.28	14.44	9.17	5.27	14.44
Sacrum	2.56	1.73	4.30	2.58	1.74	4.32
Humeri, Proximal	2.49	1.58	4.07	2.48	1.55	4.03
Humeri, Upper Shaft	1.19	0.00	1.19	1.18	0.00	1.18
Humeri, Lower Shaft	1.13	0.00	1.13	1.11	0.00	1.11
Humeri, Distal	1.89	1.86	3.75	1.89	1.87	3.76
Radii, Proximal	0.41	0.64	1.05	0.41	0.64	1.04
Radii, Shaft	0.69	0.00	0.69	0.68	0.00	0.68
Radii, Distal	0.71	0.90	1.61	0.70	0.88	1.59
Ulnae, Proximal	1.01	0.95	1.95	1.00	0.92	1.93
Ulnae, Shaft	0.87	0.00	0.87	0.86	0.00	0.86
Ulnae, Distal	0.50	0.94	1.45	0.49	0.96	1.45
Wrists and Hands	2.43	3.90	6.33	2.44	3.71	6.15
Femora, Proximal	4.05	2.61	6.66	4.03	2.60	6.63
Femora, Upper Shaft	2.44	0.00	2.44	2.42	0.00	2.42
Femora, Lower Shaft	3.81	0.00	3.81	3.78	0.00	3.78
Femora, Distal	3.35	2.45	5.80	3.35	2.46	5.80
Patellae	0.14	0.13	0.26	0.14	0.13	0.26
Tibiae, Proximal	2.92	1.73	4.65	2.88	1.76	4.65
Tibiae, Shaft	2.67	0.00	2.67	2.70	0.00	2.70
Tibiae, Distal	1.76	1.61	3.36	1.74	1.62	3.36
Fibulae, Proximal	0.36	0.68	1.05	0.35	0.69	1.04
Fibulae, Shaft	0.66	0.00	0.66	0.67	0.00	0.67
Fibulae, Distal	0.57	0.89	1.46	0.58	0.88	1.46
Ankles and Feet	3.85	4.13	7.98	3.54	3.70	7.23
Cranial Cartilage	N/A	9.40	N/A	N/A	9.47	N/A
Costal Cartilage	N/A	10.60	N/A	N/A	10.53	N/A
CV Intervertebral Discs	N/A	0.19	N/A	N/A	0.17	N/A
TV Intervertebral Discs	N/A	0.61	N/A	N/A	0.58	N/A
LV Intervertebral Discs	N/A	0.41	N/A	N/A	0.42	N/A
Total Skeleton (cm³)	162.73	116.22	278.95	162.17	114.91	277.08
Mass(g)	239.38	127.84	367.22	238.55	126.40	364.95
Reference Mass (g)	240.00	127.32	367.32	240.00	127.32	367.32
Ratio	1.00	1.00	1.00	0.99	0.99	0.99

[1]Total bone includes contributions of cranial, costal, and intervertebral disc cartilage

[2]This volume is NURBS, while all others are polygon mesh





Bone Site	Cartilage Volume Fraction (CVF)	Cortical Bone Volume Fraction (CBVF)	Spongiosa Volume Fraction (SVF)	Marrow Volume Fraction (MVF)	Trabecular Bone Volume Fraction (BVF)
[1]Avg. Cervical	0.6988	0.0862	0.2150	0.4422	0.5578
[2]Avg. Thoracic	0.6988	0.0862	0.2150	0.4224	0.5776
[3]Avg. Lumbar	0.6988	0.0862	0.2150	0.5027	0.4973
[4]Avg. Rib	0.2626	0.3760	0.3614	0.6059	0.3941
[5]Avg. Sternum	0.5993	0.1451	0.2557	0.6098	0.3902
[6]Avg. Iliac Crest	0.3511	0.1943	0.4545	0.6422	0.3578

[1]Linear average between 5 day C3, C4, C5, C6, C7 MVF (+/- 0.0324), 4 Day L3 segmented

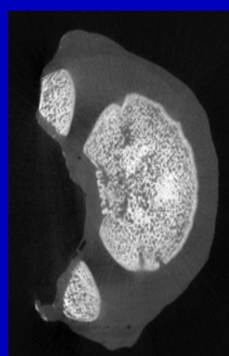
[2]Linear average between 5 day T1, T2, T3, T4, T5, T10, T11, T12 and 4 day T9, T10, T11, T12 MVF (+/-0.1177) , 4 Day L3 segmented

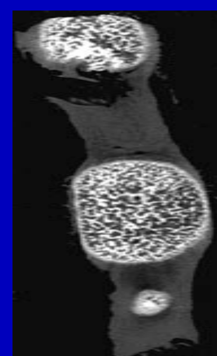
[3]Linear average between 5 day L1, L2, L3, L4, L5 and 4 day L2, L3, L4, L5 MVF (+/- 0.0572), 4 Day L3 segmented

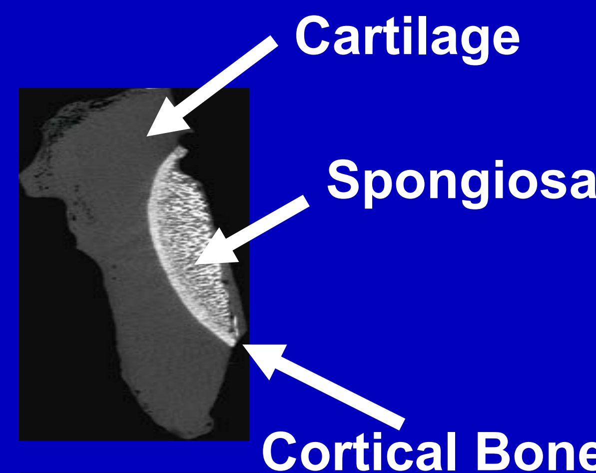
[4]Linear average between 5 day rib 4 and 4 day right/left rib 2 MVF (+/- 0.0894), 5 Day rib 4 segmented

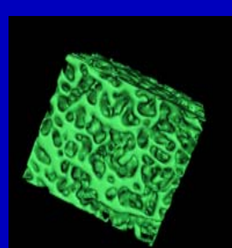
[5]4 day sternum

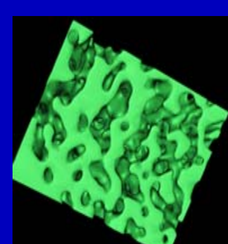
[6]5 day iliac crest

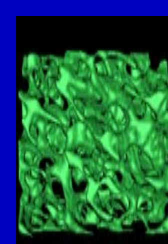


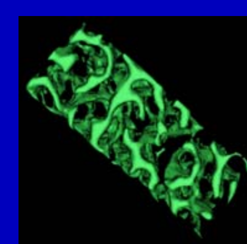












Skeletal Site	NURBS/Polygon Mesh (%)	ICRP 89, Table 9.4 (%)	Difference (abs. %)
Cranium	28.61	27.00	-1.61
Mandible	3.21	2.50	-0.71
Cervical	2.09	3.40	1.31
Thoracic	3.60	8.30	4.70
Lumbar	2.40	2.40	0.00
Sternum	0.63	0.00	-0.63
Ribs	14.89	9.20	-5.69
Scapulae	2.91	2.70	-0.21
Clavicles	1.20	0.80	-0.40
Os coxae	6.26	9.20	2.94
Sacrum	0.96	0.10	-0.86
Humeri, Proximal	1.84	2.30	-0.42
Humeri, Upper Shaft	0.89		
Humeri, Lower Shaft	0.84	2.30	-0.23
Humeri, Distal	1.69		
Radii, Proximal	0.47		
Radii, Shaft	0.52	1.25	-0.46
Radii, Distal	0.73		
Ulnae, Proximal	0.88		
Ulnae, Shaft	0.65	1.25	-0.93
Ulnae, Distal	0.65		
Wrists and Hands	2.85	3.60	0.75
Femora, Proximal	3.00	3.70	-1.12
Femora, Upper Shaft	1.82		
Femora, Lower Shaft	2.84	3.70	-1.75
Femora, Distal	2.62		
Patellae	0.12	2.67	2.55
Tibiae, Proximal	2.10		
Tibiae, Shaft	1.99	2.67	-2.94
Tibiae, Distal	1.52		
Fibulae, Proximal	0.47		
Fibulae, Shaft	0.49	2.67	1.04
Fibulae, Distal	0.66		
Ankles and Feet	3.60	8.30	4.70
Total	100.00	100.00	0.00

Skeletal Site	Newborn		Adult		RATIOS
	Cortical	Trabecular	Cortical	Trabecular	Newborn/Adult
[1]Cranium	0.95	0.05	0.95	0.05	1.00
[2]Mandible	0.78	0.22	0.95	0.05	0.82
[3]Cervical	0.47	0.53	0.25	0.75	1.88
[3]Thoracic	0.47	0.53	0.25	0.75	1.88
[3]Lumbar	0.47	0.53	0.34	0.66	1.38
[4]Sternum	0.59	0.41	0.94	0.06	0.63
[2]Ribs	0.78	0.22	0.94	0.06	0.83
[5]Scapula	0.51	0.49	0.94	0.06	0.55
[5]Clavicles	0.51	0.49	0.94	0.06	0.55
[5]Os coxae	0.51	0.49	0.90	0.10	0.57
[3]Sacrum	0.47	0.53	0.75	0.25	0.63
[2]Humeri, upper half	0.78	0.22	0.90	0.10	0.86
[2]Humeri, lower half	0.78	0.22	0.90	0.10	0.86
[2]Radii	0.78	0.22	0.87	0.13	0.89
[2]Ulna	0.78	0.22	0.87	0.13	0.89
[2]Wrist and Hands	0.78	0.22	0.95	0.05	0.82
[2]Femora, upper half	0.78	0.22	0.77	0.23	1.01
[2]Femora, lower half	0.78	0.22	0.77	0.23	1.01
[2]Patella	0.78	0.22	0.77	0.23	1.01
[2]Tibia	0.78	0.22	0.83	0.17	0.94
[2]Fibula	0.78	0.22	0.89	0.11	0.87
[2]Ankles and Feet	0.78	0.22	0.65	0.35	1.20

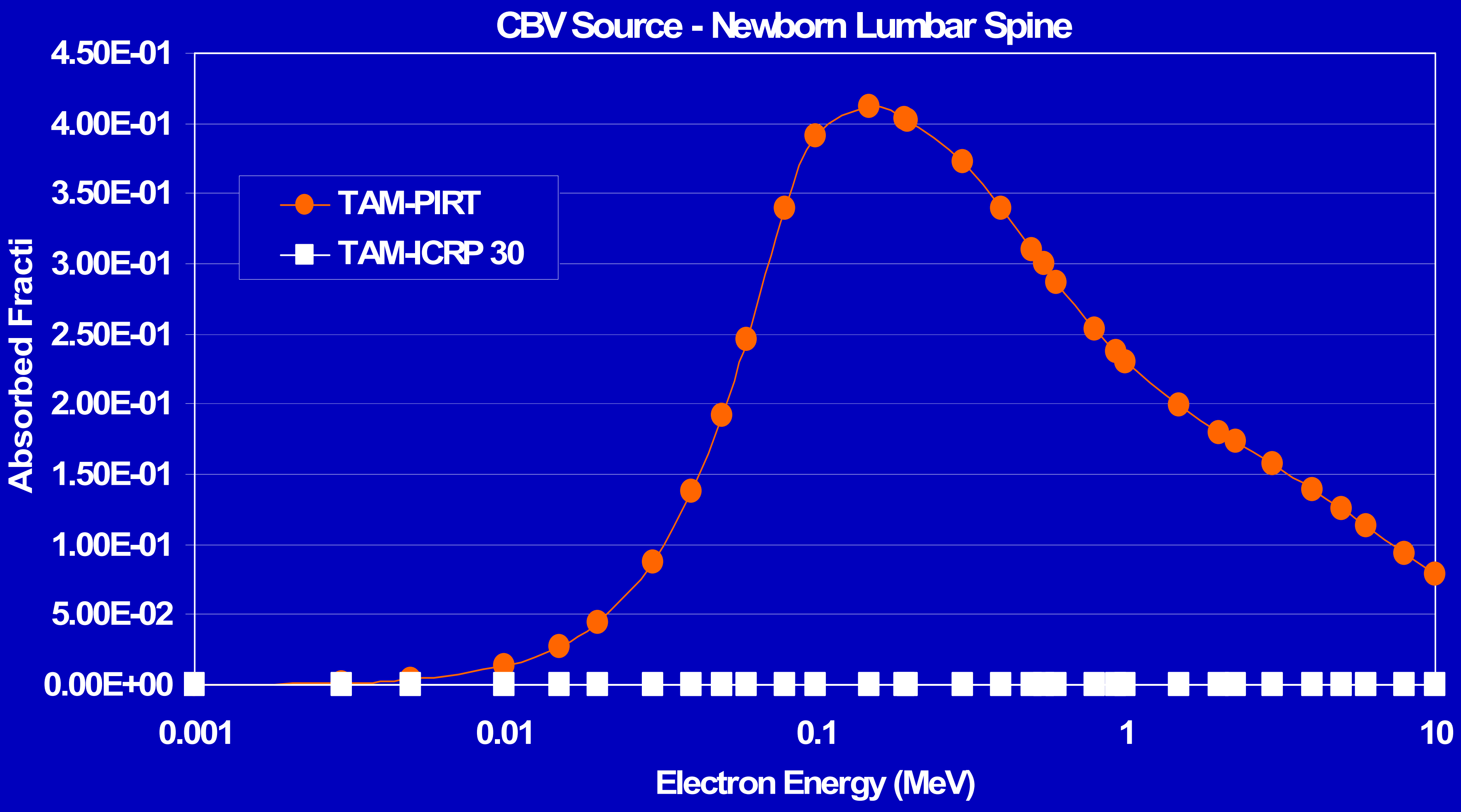
[1]Adult value used as default

[2]100% 5 day old 4th rib

[3]100% 4 day old 3rd lumbar vertebra

[4]100% 4 day old sternum

[5]60:40 5 day old iliac crest to 4 day old 3rd lumbar vertebra


CBV Source - Newborn Lumbar Spine
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4.00E-01
3.50E-01
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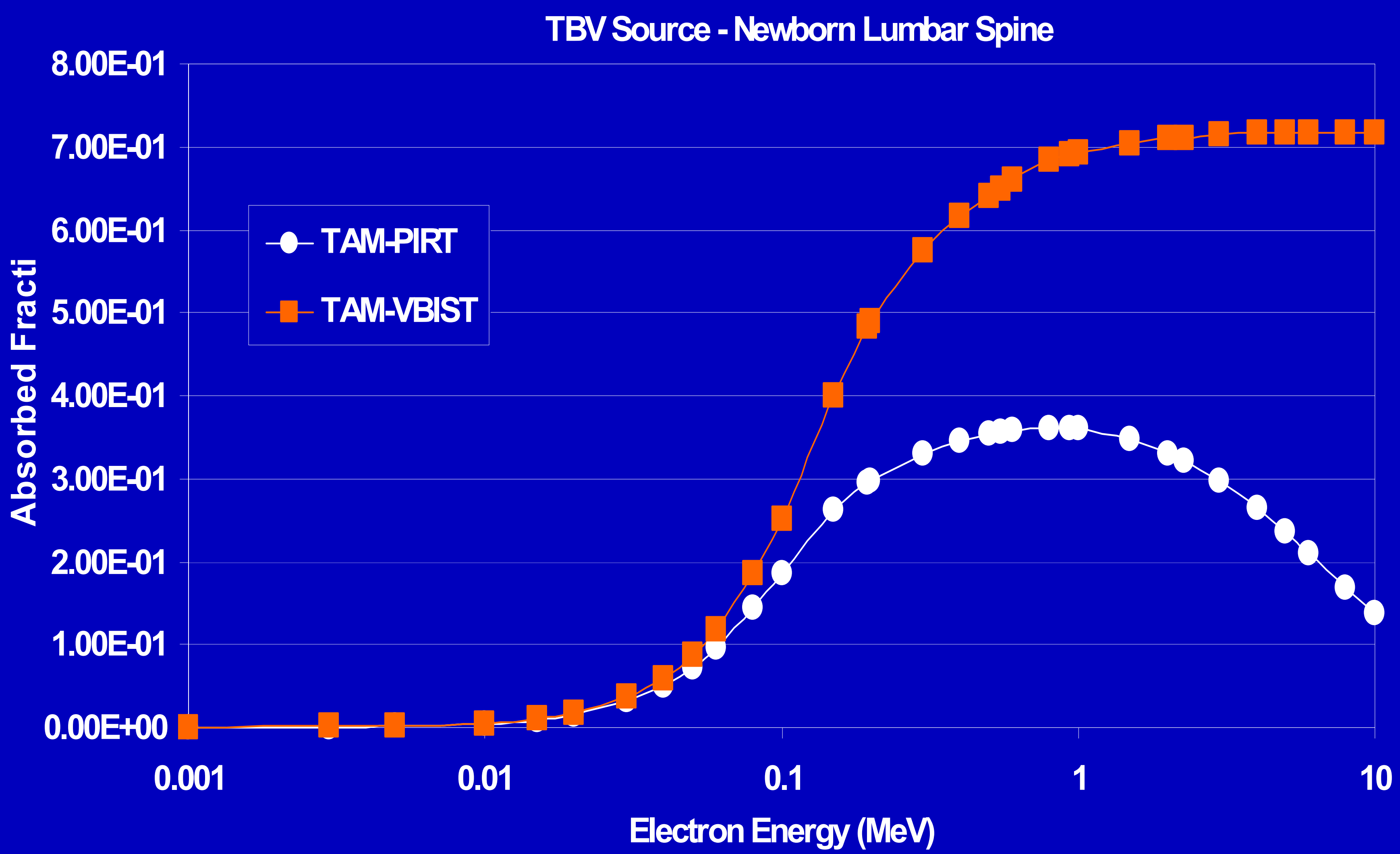
5.00E-02
0.00E+00
Absorbed Fracti
TAM-PIRT
TAM-ICRP 30
0.001
0.01
0.1
1
10
Electron Energy (MeV)



TBV Source - Newborn Lumbar Spine
8.00E-01
7.00E-01
6.00E-01
5.00E-01
4.00E-01
3.00E-01
2.00E-01
1.00E-01
0.00E+00
Absorbed Fracti
TAM-PIRT
TAM-VBIST
0.001
0.01
0.1
1
10
Electron Energy (MeV)

Conclusions

- **Newborn homogeneous skeleton using NURBS/Polygon Mesh**
  - **Hybrid of stylized and voxel phantom advantages**
- **High resolution microCT of 3D microstructure**
  - **Hybrid of stylized and voxel phantom advantages**
- **Electron dosimetry**
  - ***EGSnrc***
  - ***PIRT* (coupled macro and micro)**
- **Diverse dosimetry applications (medical physics, health physics, medical health physics, dose reconstruction, etc…)**

What's Next???

- Complete remaining skeletal sites
- Compare skeletal-averaged results with Stabin/Siegel
- Improve photon fluence-to-dose response functions
  - Model flux depression across cortical bone
    - Current 1985 Eckerman model transports in homogeneous bone
  - Full spatial transport of the secondary electrons within the trabecular spongiosa
    - Current 1985 Eckerman model does not account for electron escape
- Complete ICRP age series (1-year, 5-year, 10-year, 15-year male and female) skeletal models and merge with whole body models

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GO GATORS!!!!