Personalized Dosimetry in the Age of AI: A Multi-Physics Framework Integrating Machine Learning and Monte Carlo for Radioactive Aerosol Exposure Assessment

Council on Ionizing Radiation Measurements & Standards

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April 29, 2024

RED^2
RADIOLOGICAL ENGINEERING, DETECTION, AND DOSIMETRY

Georgia Tech | George W. Woodruff School of Mechanical Engineering

RED^2 Laboratory – Overview and Collaborations

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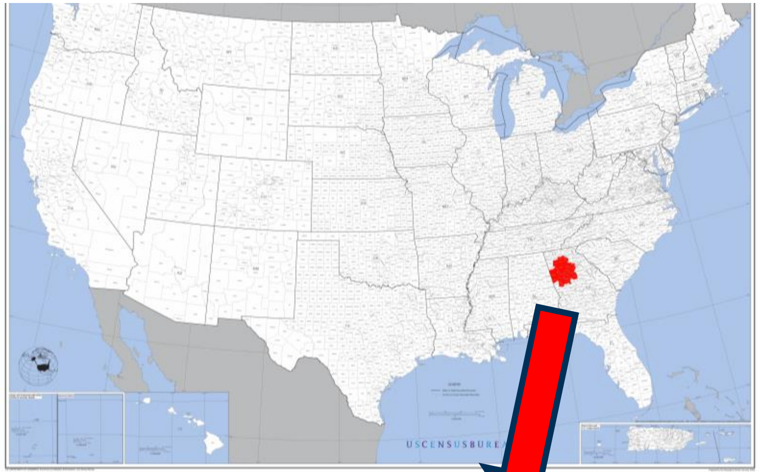

- **Spring 2024 Research Group**
- 10 Ph.D. students in NRE and MP
- 3 M.S. students
- 6 Undergraduate students
- 1 Post-doctoral Fellow
- 1 Research Engineer
- 1 Visiting Professor

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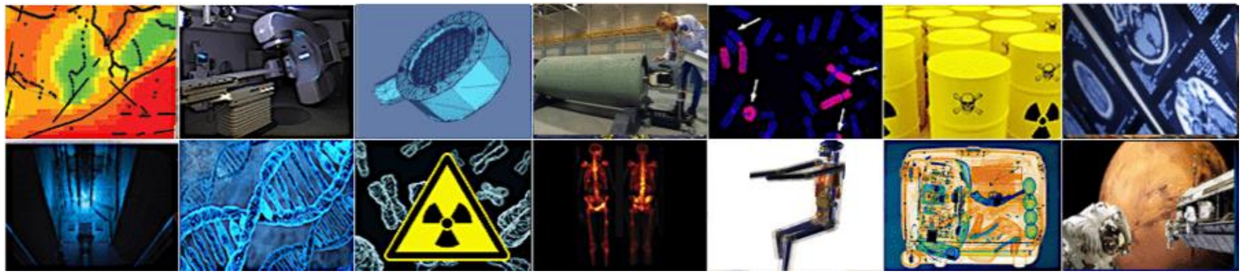
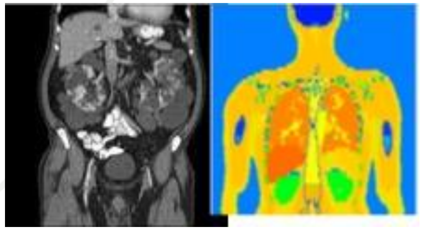
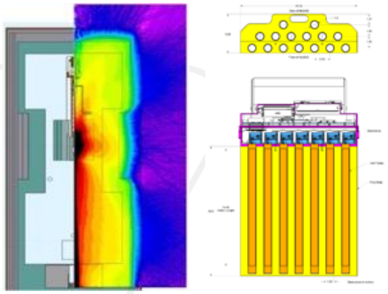
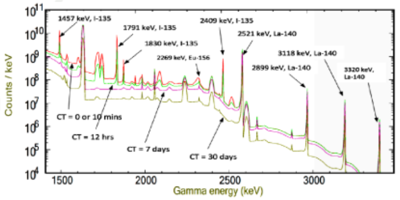
Radiological Engineering, Detection, and Dosimetry



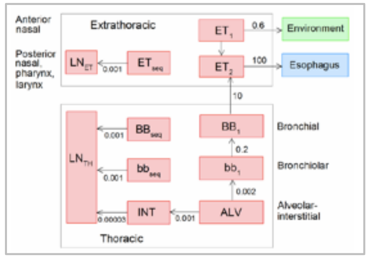
Mission: The **Radiological Engineering, Detection, and Dosimetry (RED²) Laboratory**, led by **Dr. Shaheen Dewji**, conducts innovative, interdisciplinary research focusing on harnessing both computational capabilities in Monte Carlo radiation transport modeling and experimental measurements for applications in radiation detection, radiation protection and shielding, dosimetry, health physics, and nuclear materials accounting.

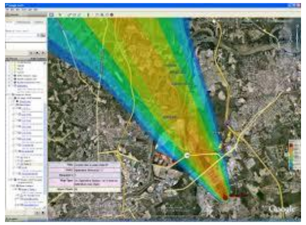






Computational Dosimetry and Shielding	Development of dose coefficients and shielding design using Monte Carlo radiation transport codes	Age/sex-specific anthropomorphic computational phantoms	Radionuclide biokinetic models for emergency response and nuclear medicine
Radiation Detection	Employment of validation and verification of gamma-ray spectroscopic detector responses	Contaminated environmental media for environmental assessment and decommissioning	Field triage of uptake during nuclear, radiological, and fission product release events
Nuclear Nonproliferation and 3S (Safety, Security & Safeguards)	Nuclear materials control, accounting, and safeguards of SNM	Gamma-ray spectroscopic analysis for safeguards by design of of advanced non-LWR reactors	Neutron multiplicity counting for field search/detection and criticality safety





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RED² Laboratory – Research Collaborations

Thrust Area 1: Computational Dosimetry

- Evaluation of Exposure Pathway, Internalized Uptakes, and Dosimetry for Military Personnel from Radiological and Toxic Metal Sources
- Uncertainty Analysis of Dose Coefficients for Nuclear Incident Response
- Low Dose Exposure Evaluation on Human Population Health
- Enhancement of Biokinetics using Physiologically-Based Models for Internalized Radionuclides

Thrust Area 2: Radiation Detection

- Evaluation of Exposure Pathway, Internalized Uptakes, and Dosimetry for Military Personnel from Radiological and Toxic Metal Sources
- A Hybrid Radiation Transport Detector Response Function Methodology for Modeling Contaminated Sites
- Neutron dosimetry and Assay with a Portable Neutron Multiplicity Detector

Thrust Area 3: Radiation Shielding

- Shielding Design And Optimization Of Novel MV Photon Preclinical FLASH Radiotherapy System
- Activation Studies in Petawatt Laser Facilities

Thrust Area 4: Nuclear Safety, Security & Nonproliferation Policy, and Nuclear Knowledge Management

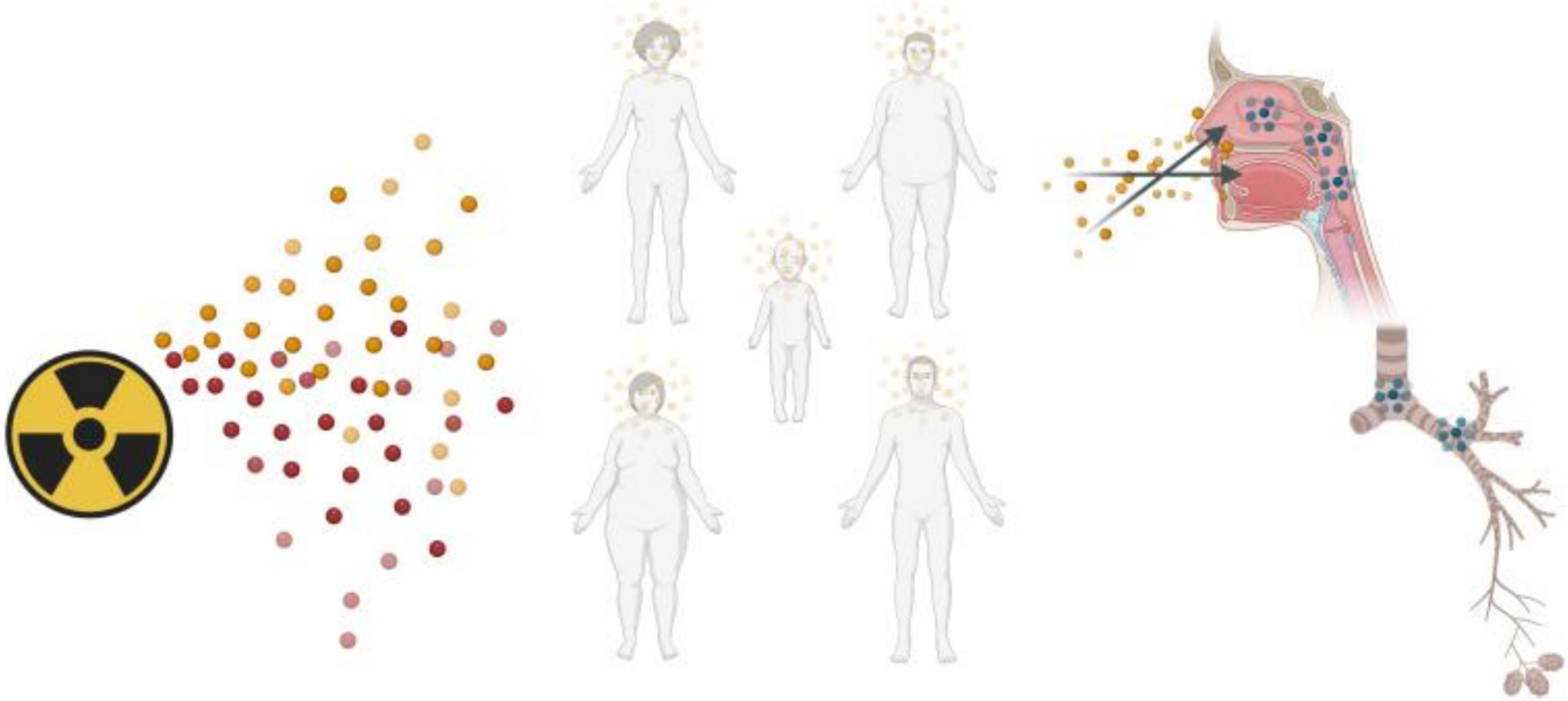
- Risk-informed Consequence-Driven Physical Protection System Optimization for Microreactor Sites
- Nuclear Material Accountancy During Disposal and Reprocessing of Molten Salt Reactor Fuel Salts

Northwestern

Feinberg School of Medicine | Radiation Oncology | Woloschak Lab Grant

Alliance for Radiological Exposures and Mitigation Science

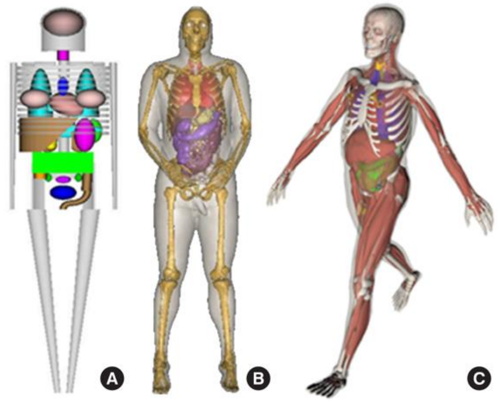
Introduction: Pathways for Internal Exposure

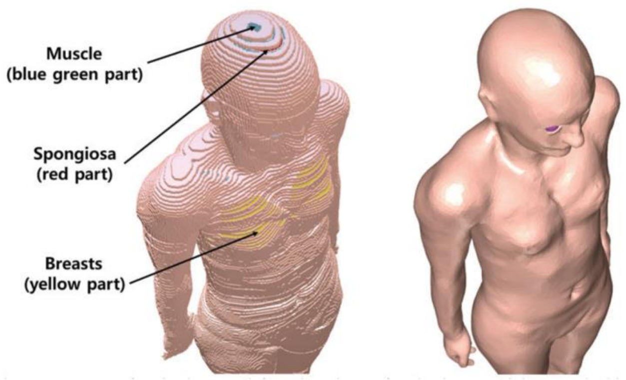


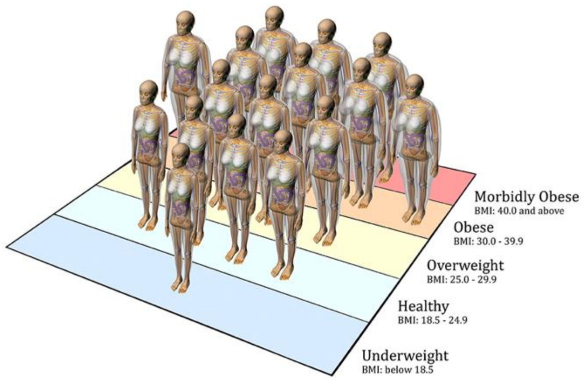
1. Radiological event
2. Aerosolized radioactive particles released from the scenario.
3. Wide range of population exposed to the radiological cloud
4. Particles entering to the HRT. CFPD analysis needed for accurate deposition profiles.

Introduction: Evolutions in Radiation Dosimetry

- Breakthroughs driven by medicine in radiation sciences
  - “Digital twins”
  - “Personalized medicine”
- Computational capabilities have afforded vast improvements in radiation modeling
  - Anatomical models (anthropomorphic phantoms)







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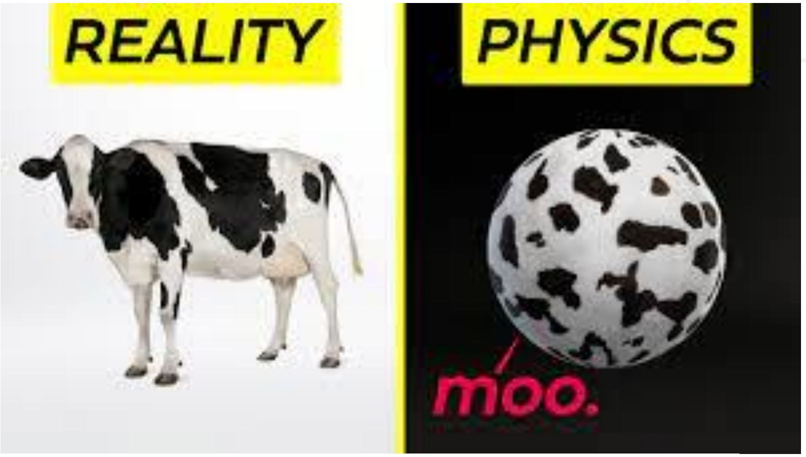
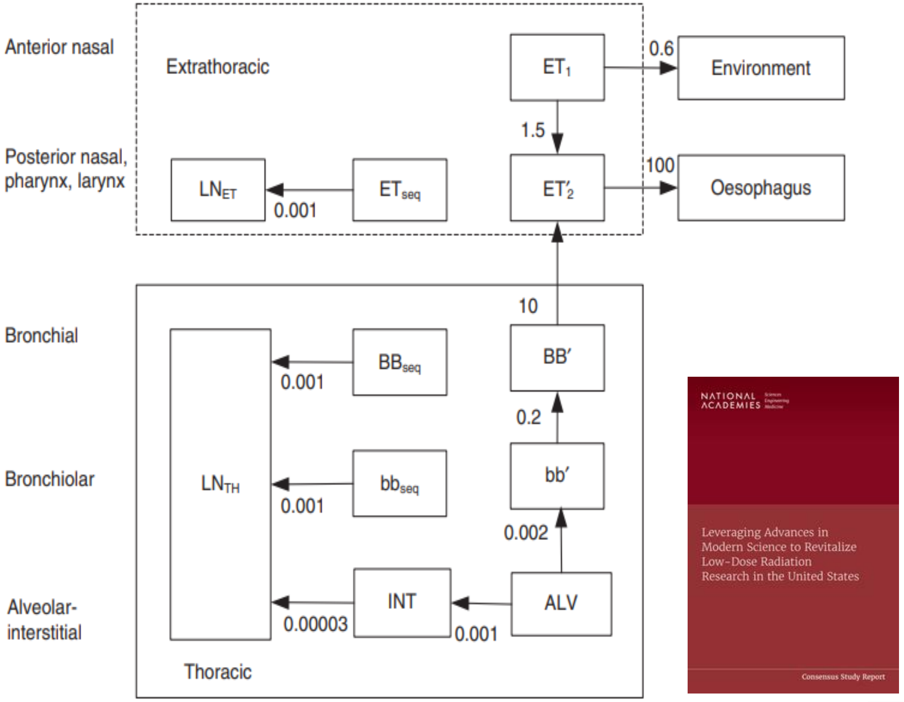
Images courtesy of G Xu (2014), W. Bolch (UF)

Introduction: Evolutions in Radiation Dosimetry

- Computational capabilities have afforded vast improvements in [radiation/biological] modeling
  - Greatest source of variability in dose assessment from internal emitters
  - Physiologically-based models of radiation behavior can also employ advanced technologies
    - Age
    - Sex
    - Non-reference
      - Height
      - Weight
      - Pregnancy





$$\dot{y} = f(t, y), \qquad t_o \leq t \leq t_{final}$$

$$y(t_o) = y_o,$$

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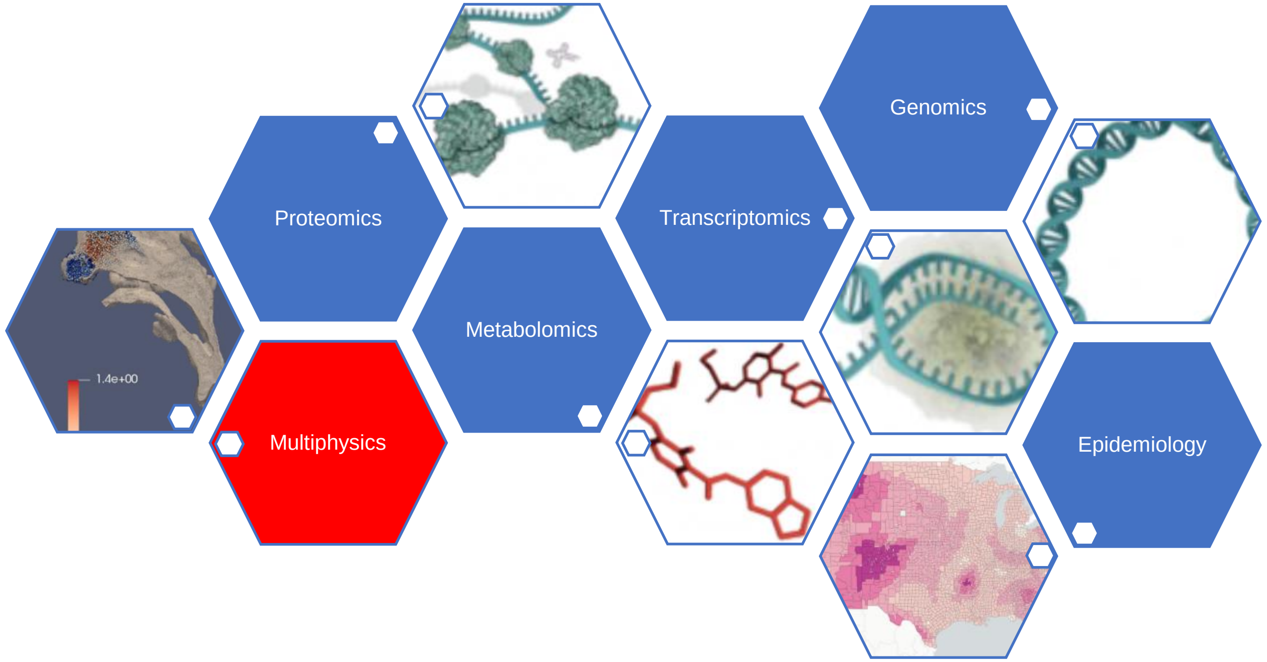
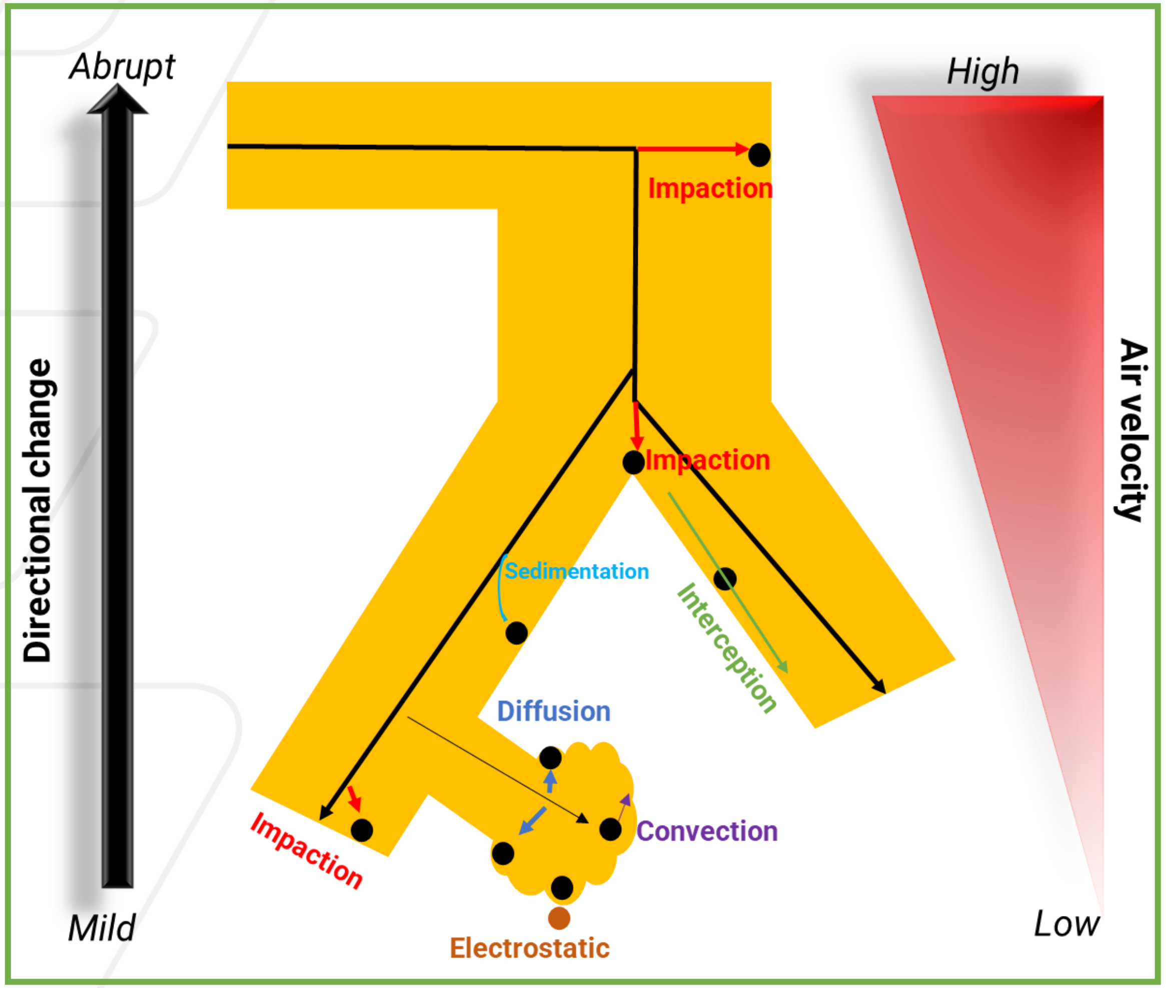
Overview: ~~Evolutions~~ Revolutions in Radiation Dosimetry

- Large and complex datasets available
- Mechanistic behavior of internalized radiation in the body can be conducted using multi-scale models

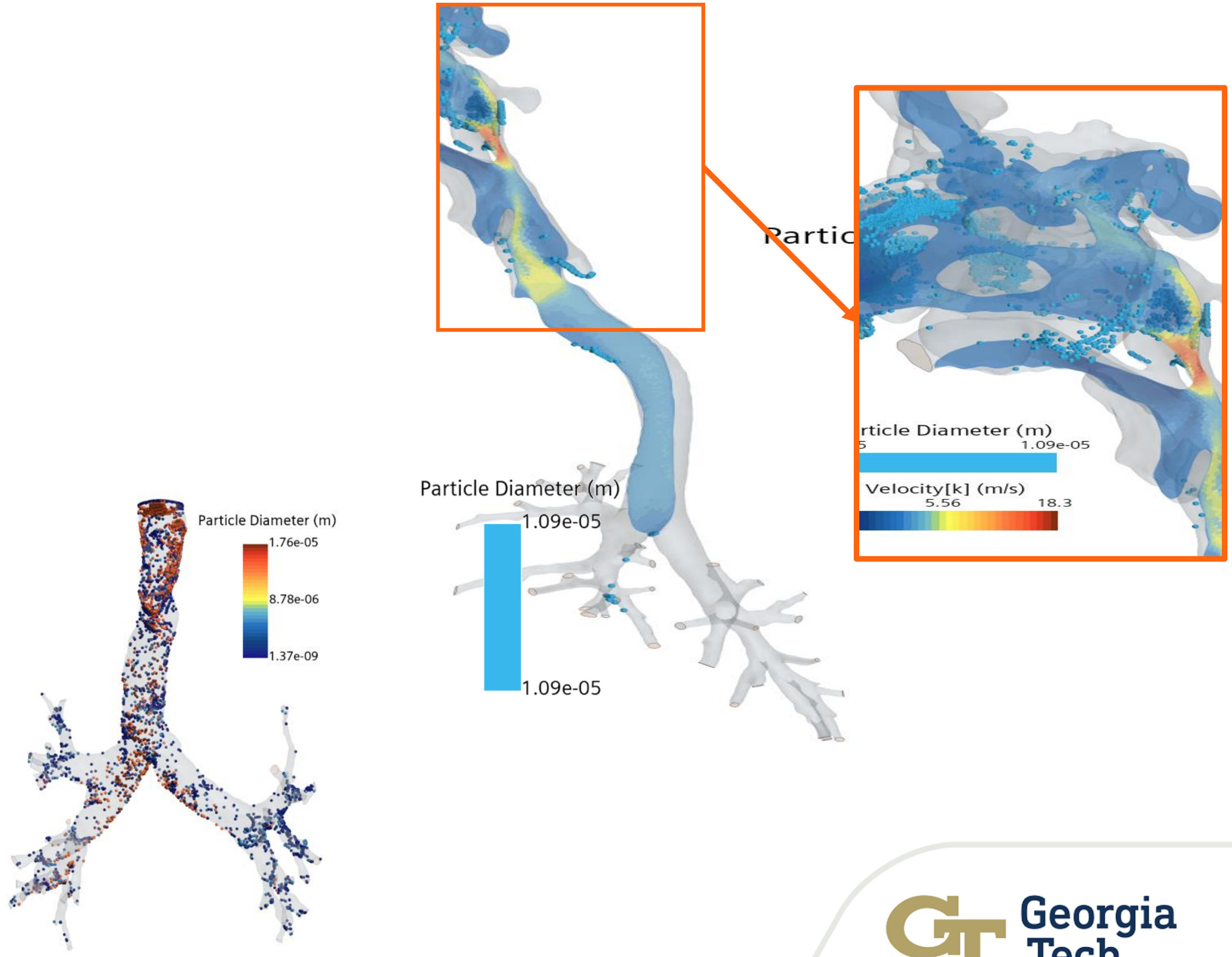


Multiphysics Modeling of Physiological Behavior

STRONTIUM-90 ICRP VS COMPUTATIONAL FLUID AND PARTICLE DYNAMICS DEPOSITION MODELING

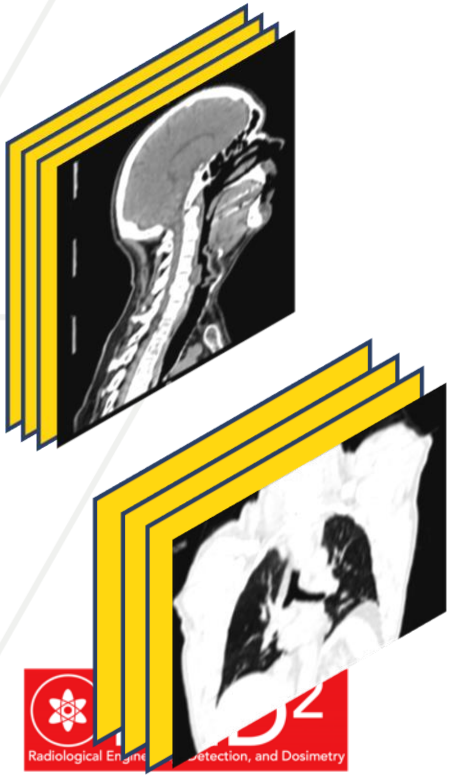


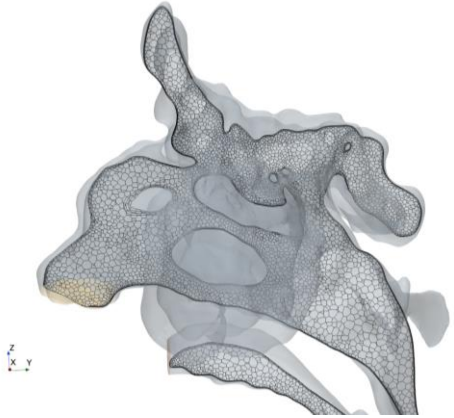
CFPD capabilities: Representative Sr-90 particle size distribution and subject-specific human respiratory tract based on CT scans

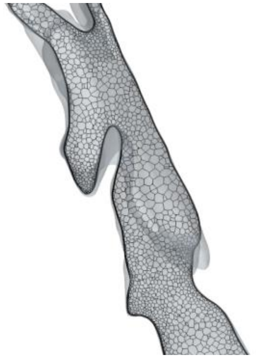


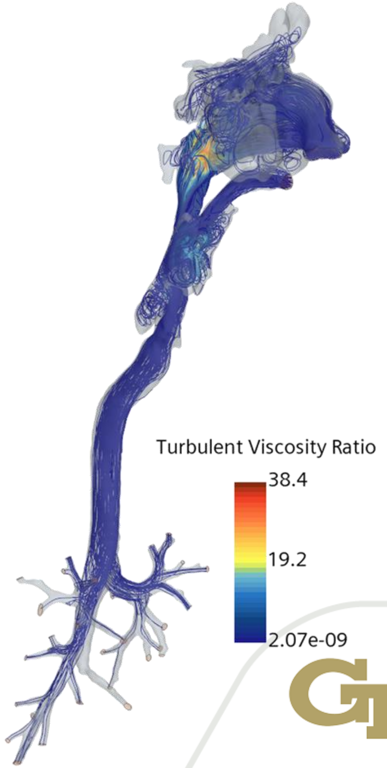
Multiphysics Modeling of Physiological Behavior:
Computational Fluid Particle Dynamics Modeling of Deposition

Chest + Neck-Head CT Scans → 3D Reconstruction → Developed automatized, open-source Python algorithms → Automated setup of CFPD simulation. →Pre-computed converged grid parameters (GCI) → CFPD simulation →Pre-validated models → **Data analysis**









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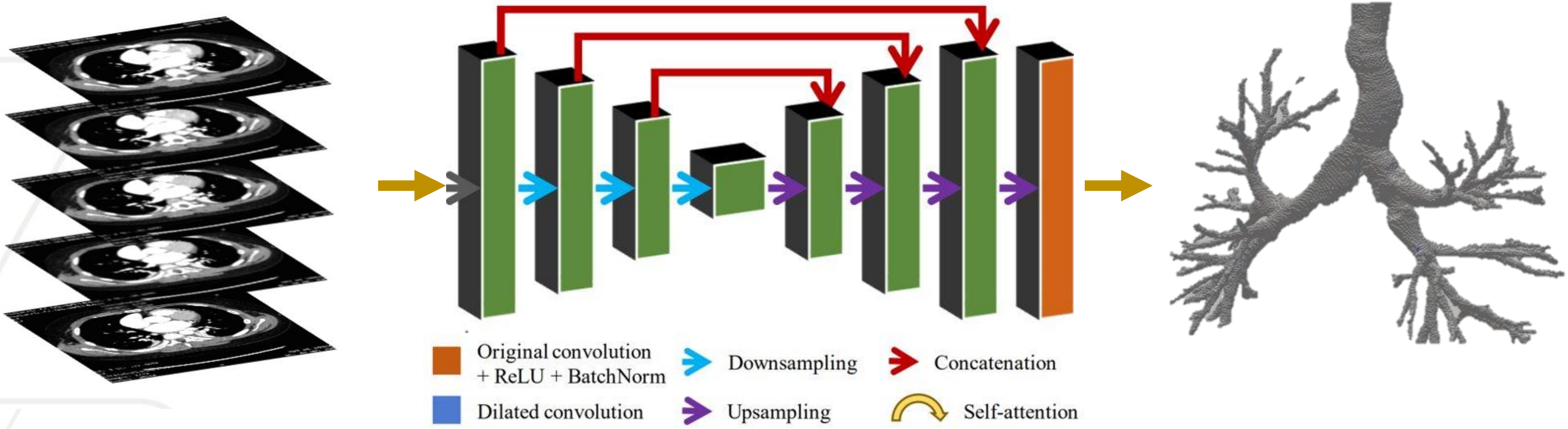
Multiphysics Modeling of Physiological Behavior: AI → CFPD

CT Segmentation - Convolutional Neural Network (CNN)



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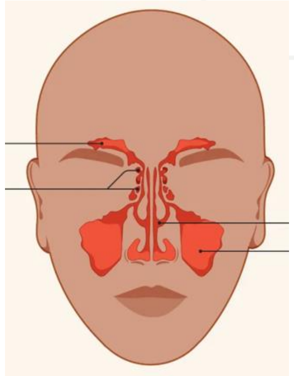
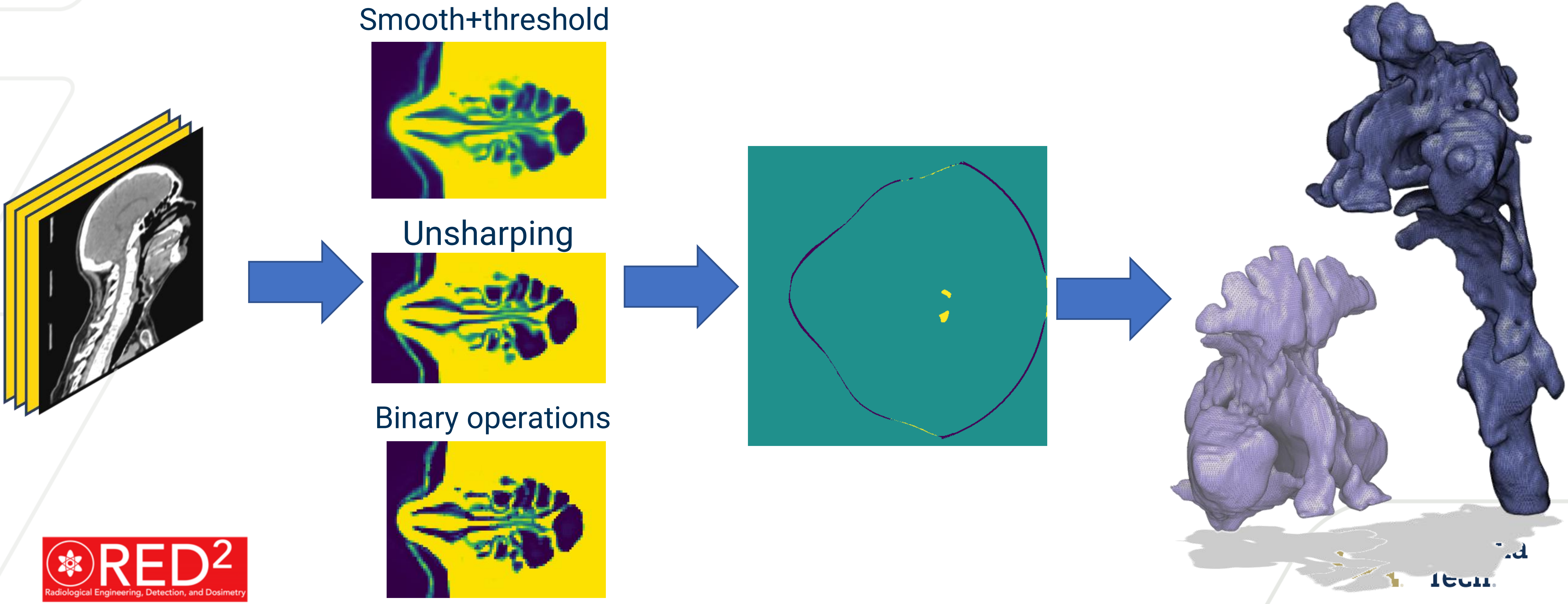
Morphological Techniques: CT Segmentation Upper HRT



Nasal cavity, automatic segmentation algorithm:

- Complex geometry
- Very challenging to capture all the sinus (in fact most of the manual segmentations by physicians does not consider some cavities)



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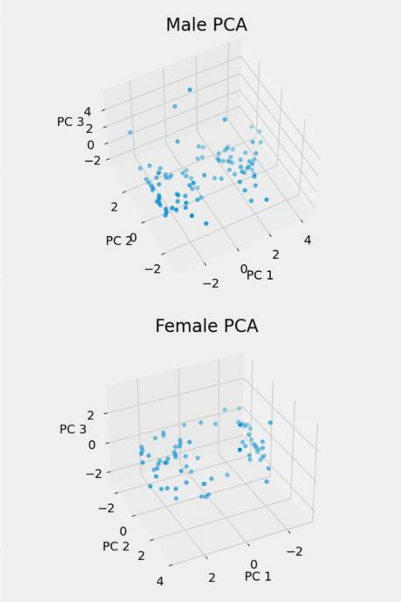
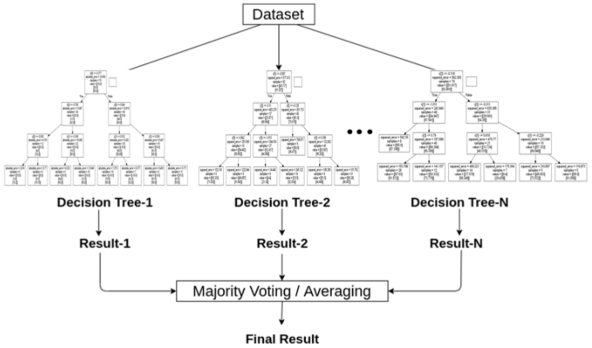
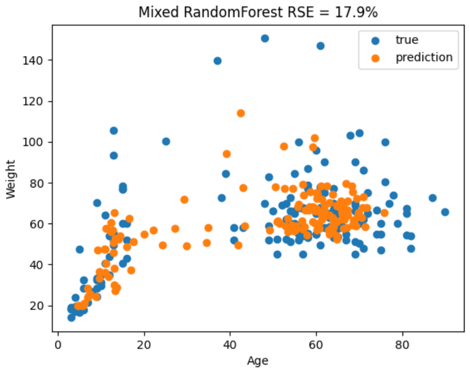
Multiphysics Modeling of Physiological Behavior: AI →CFPD

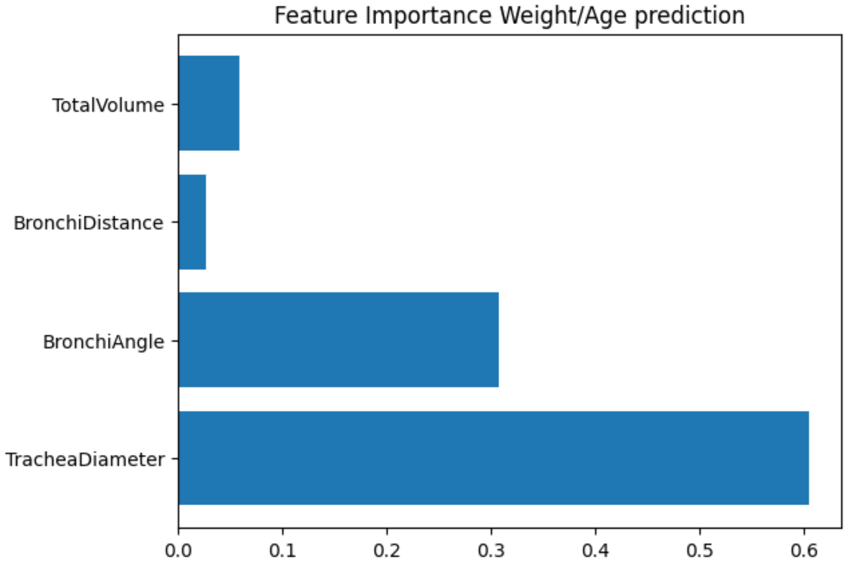
Supervised Learning: Random Forest Regressor

Trained on metrics of the respiratory tract → Extract the importance of features



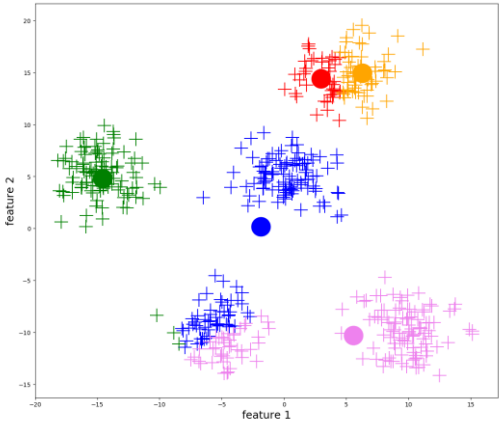






Unsupervised Learning: Kernel k-means Clustering

This algorithm makes ***K*** clusters by joining data points that are closest to each other.



(a) K-means (b) kernel K-means

k=5

Before clustering, using a function or “kernel” on the data, allows us to “linearize” non-linear patterns in data.

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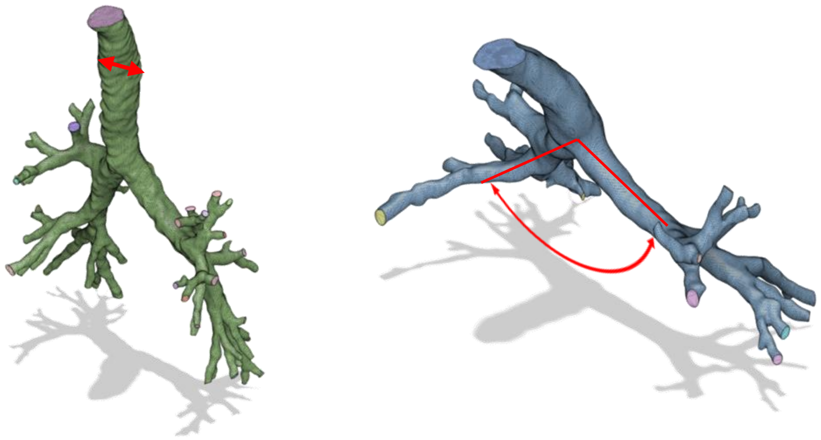
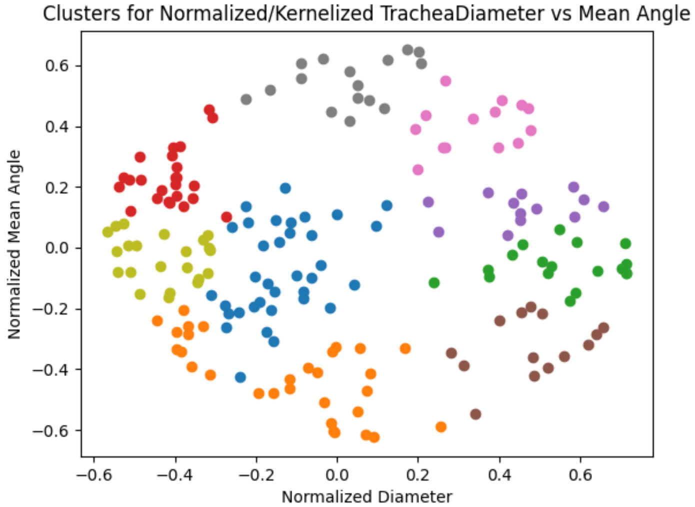
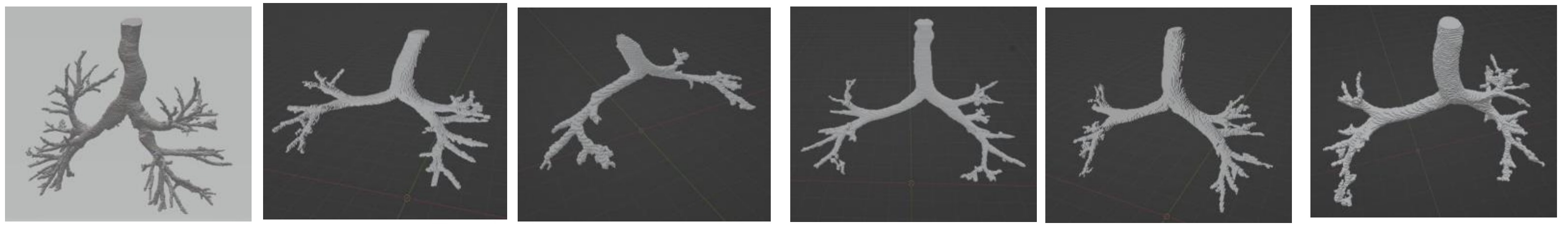
Unsupervised Learning: Kernel k-means Clustering

- Our work show that for members of the public, the metrics best that describes each airway are **Trachea Diameter** and **Bronchi Angle**







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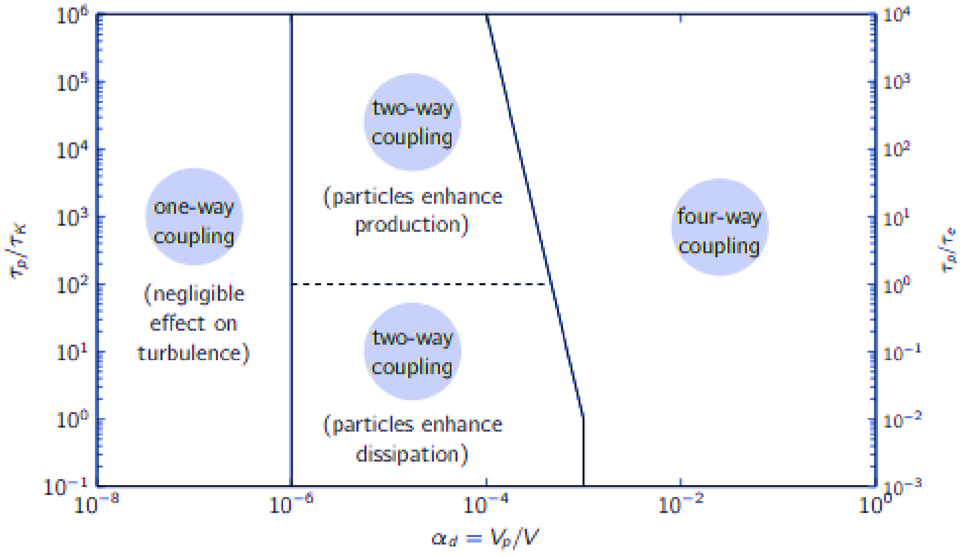
Multiphysics Modeling of Physiological Behavior: AI → CFPD

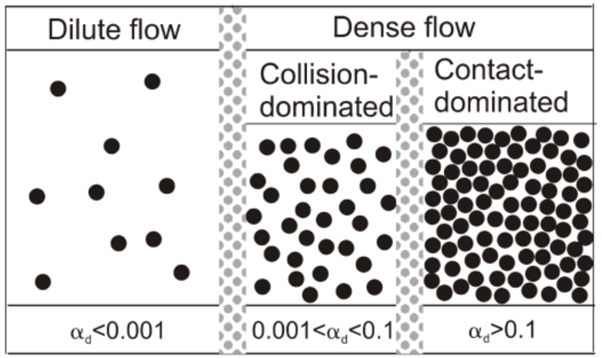
Lagrangian Particle Tracking

Laminar (Nose) → Turbulent (Trachea) → Relaminarize

- Solutions to **Navier Stokes**
  - k-omega Shear Stress Transport (SST) Langtry Menter
- Numerical technique for simulated tracking of particle paths.
- **Coupling:**
  - **2-way coupling** considering the interaction between the continuous and particulate phase only by momentum exchange terms.
  - **4-way coupling** considering particle-particle collision; momentum exchanged between the fluid and particles; and turbulence energy exchange between the gas and particles



Stokes number vs void coefficient



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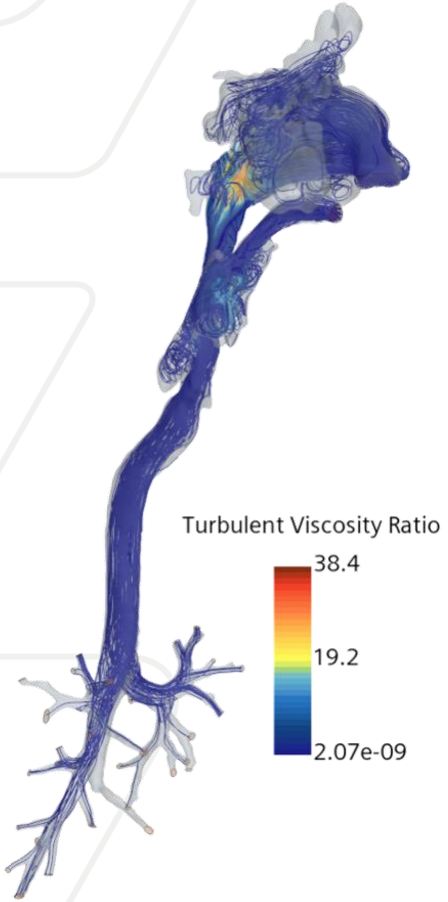
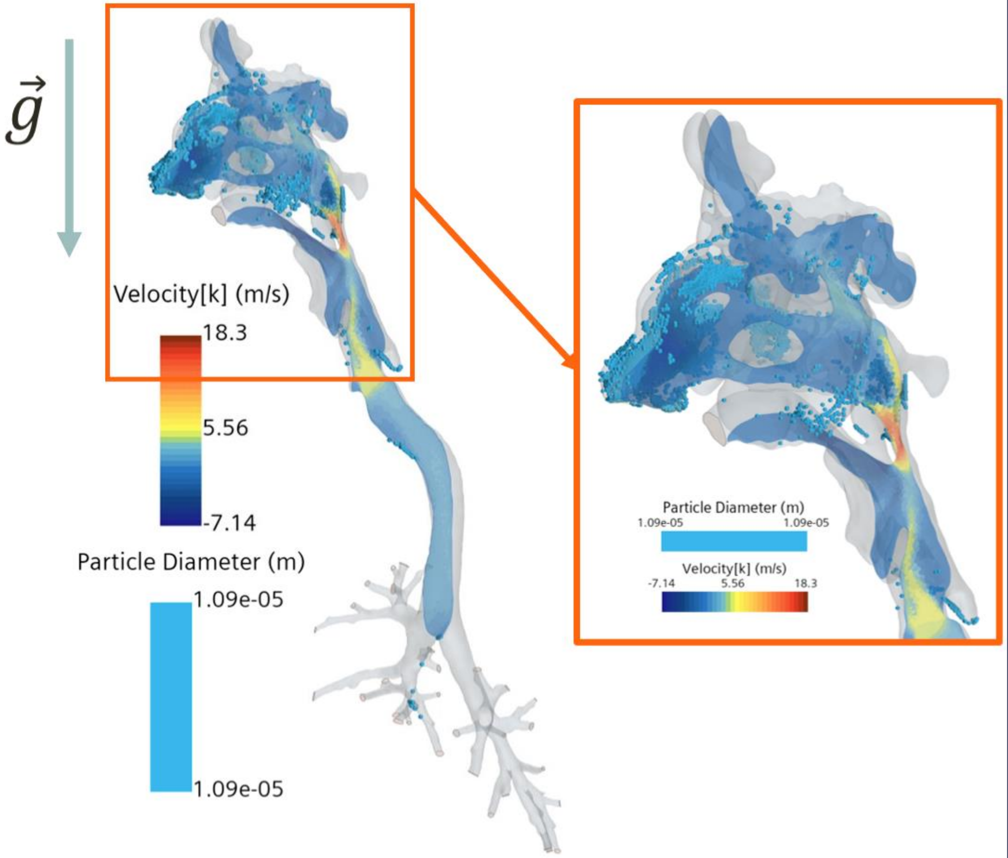
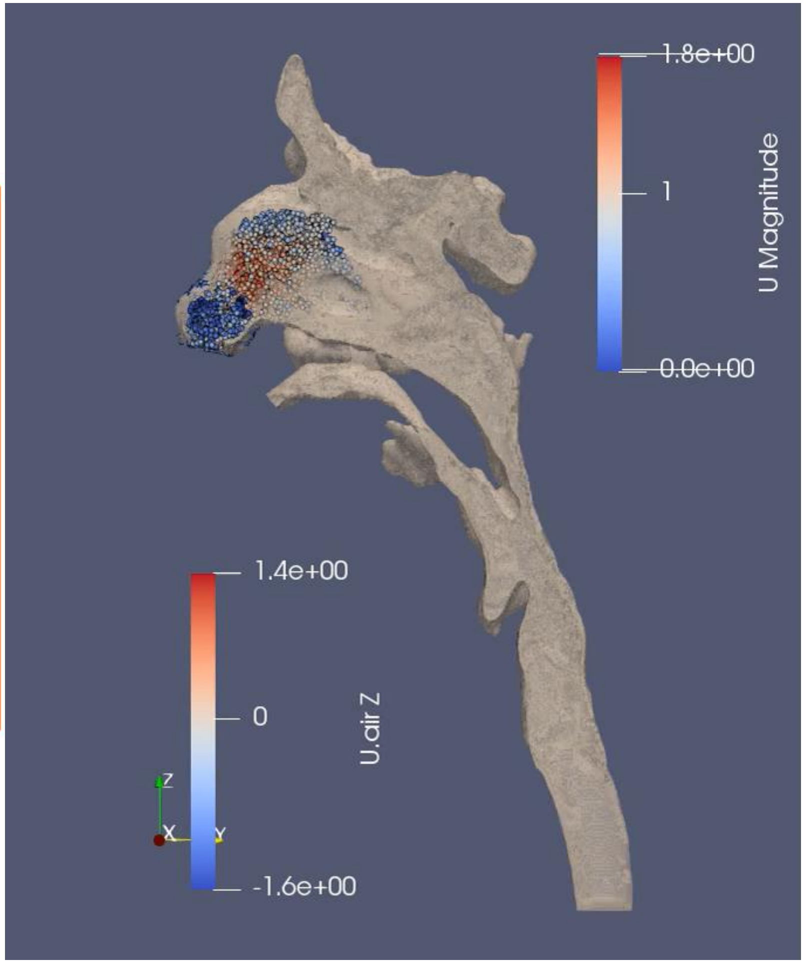
Application - Fluid and Particle Dynamics in Respiratory Tract







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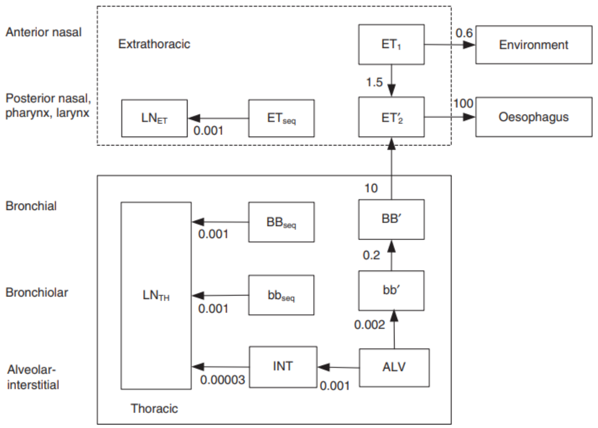
Multiphysics Modeling of Physiological Behavior: AI →CFPD

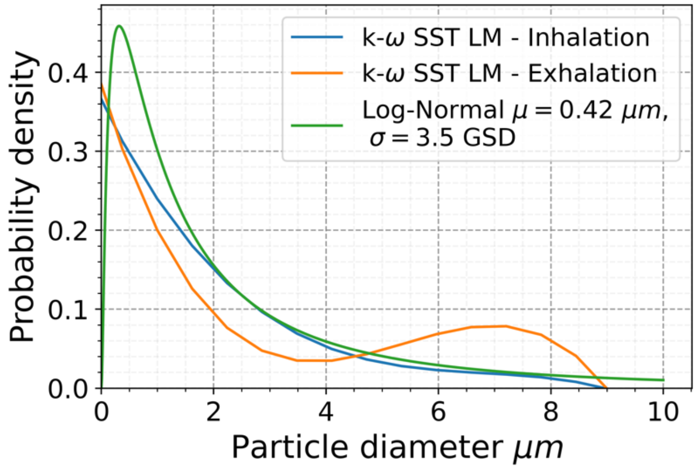
STRONTIUM-90 ICRP VS COMPUTATIONAL FLUID AND PARTICLE DYNAMICS MODELING

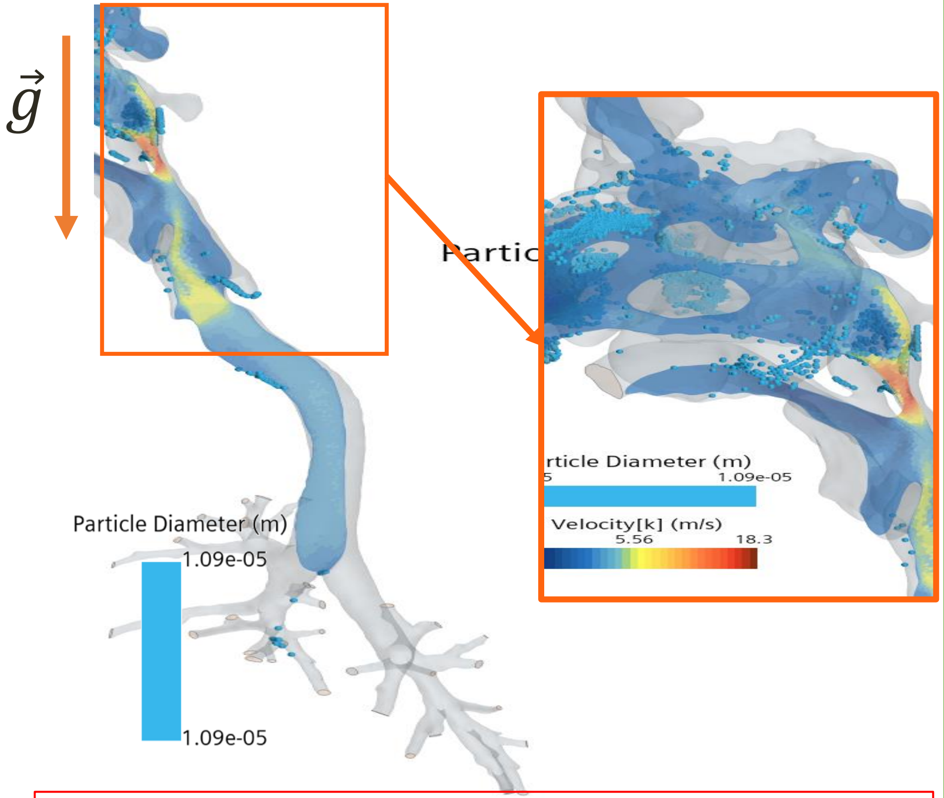
HRTM for Sr-90 from ICRP 66/130

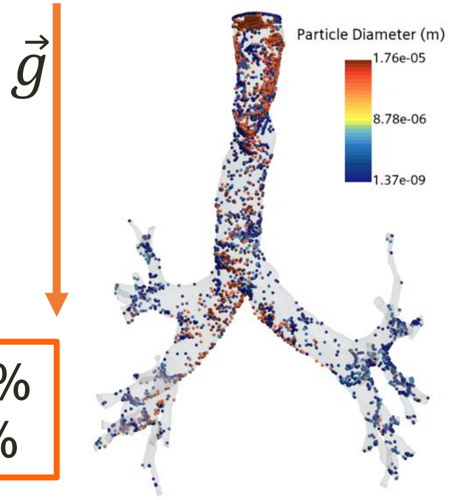


ICRP 1st order linear equation model of the HRTM + clearance to other organs

CFPD capabilities: Representative Sr-90 particle size distribution and subject-specific human respiratory tract based on CT scans







mDF=81.5%
nDF=40.9%

These inputs can then serve as a **source distribution** for a Monte-Carlo transport code. → Accurate **spatial dose distribution**

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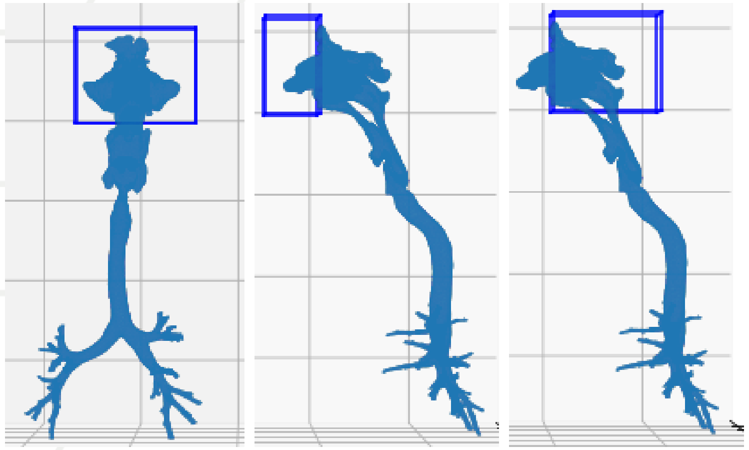
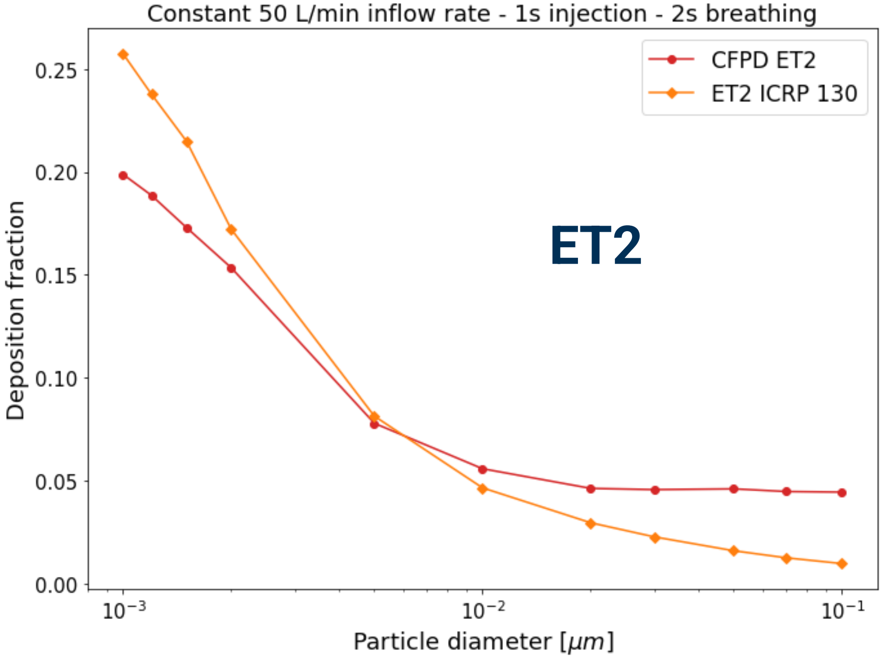
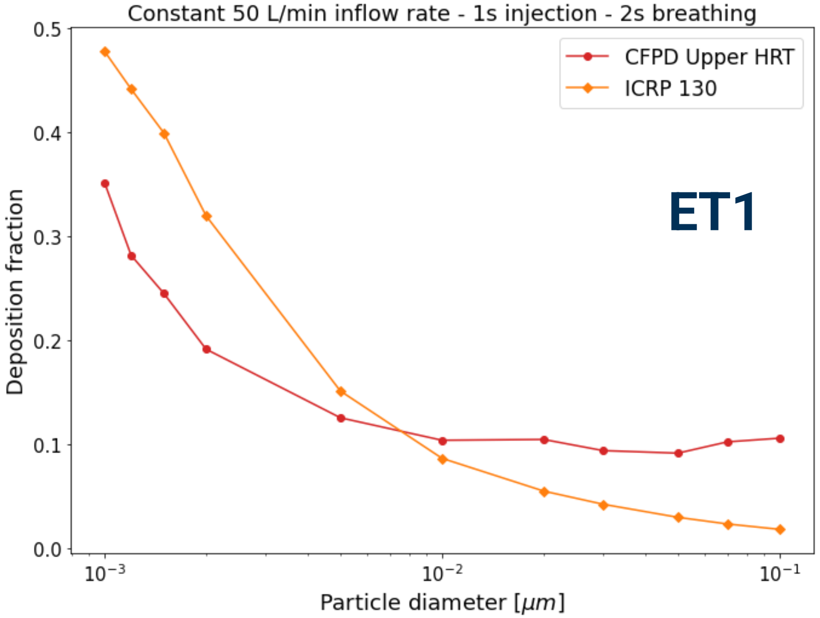
Multiphysics Modeling of Physiological Behavior: AI →CFPD Results: Deposition Fractions vs ICRP 130

ET1 ET2







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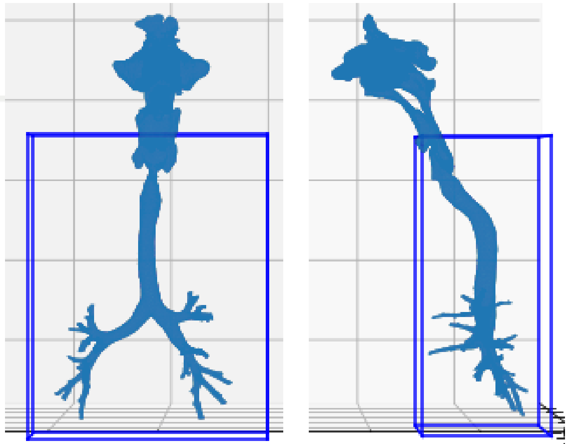

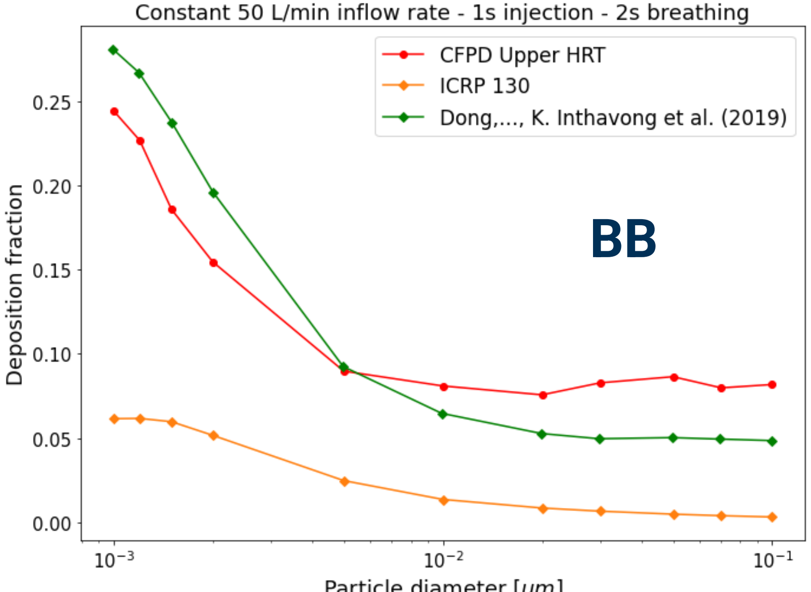

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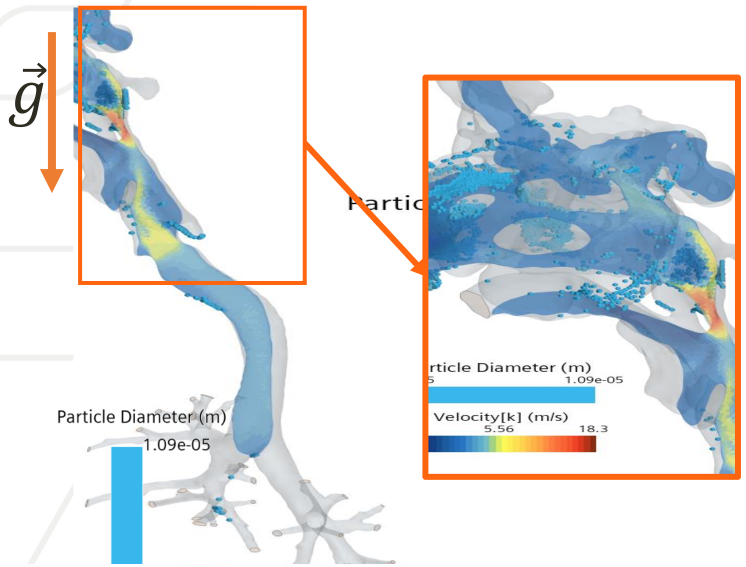
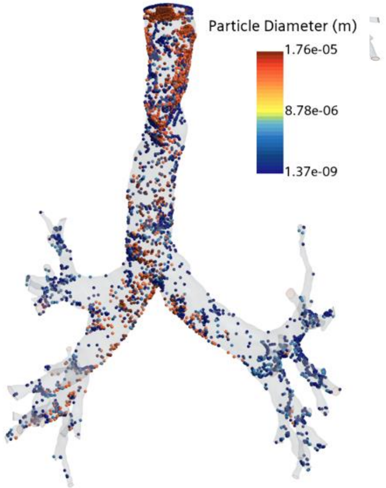
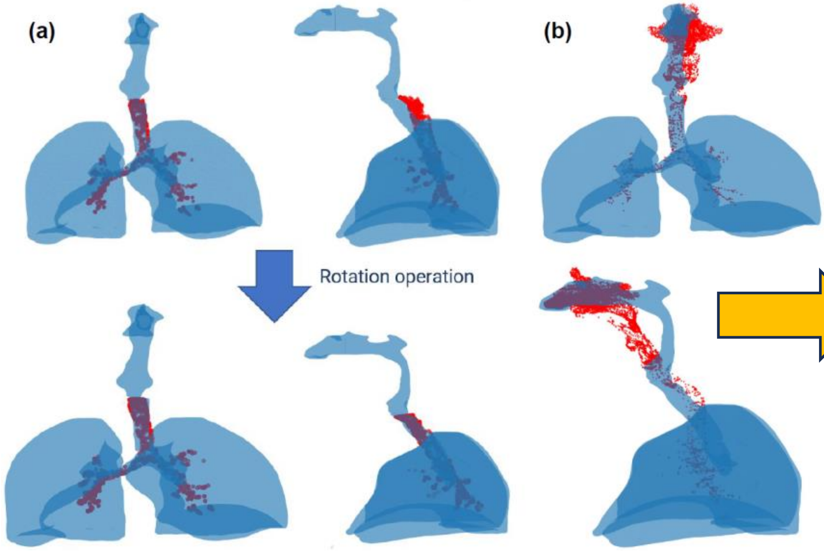
Multiphysics Modeling of Physiological Behavior: CFPD → Monte Carlo

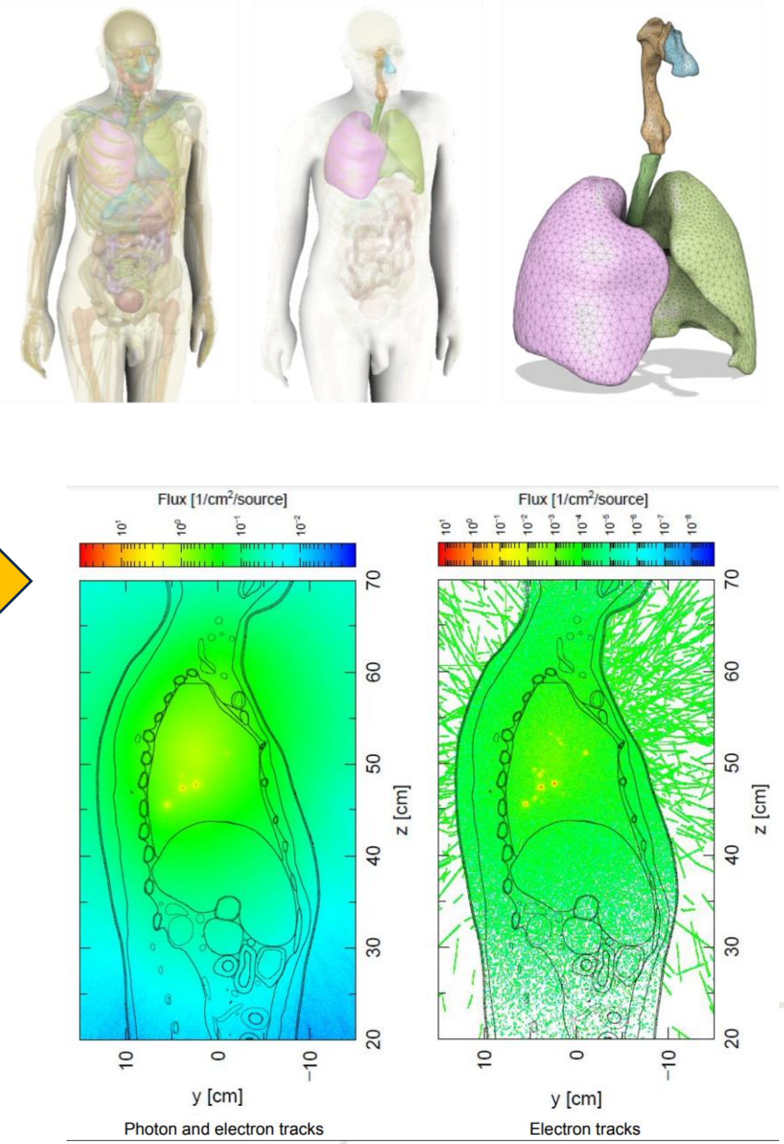
STRONTIUM-90 ICRP VS CFPD AND PHITS MONTE-CARLO SOFTWARE





These inputs can then serve as a **source distribution** for a Monte-Carlo transport code.
→ Accurate **spatial dose distribution**



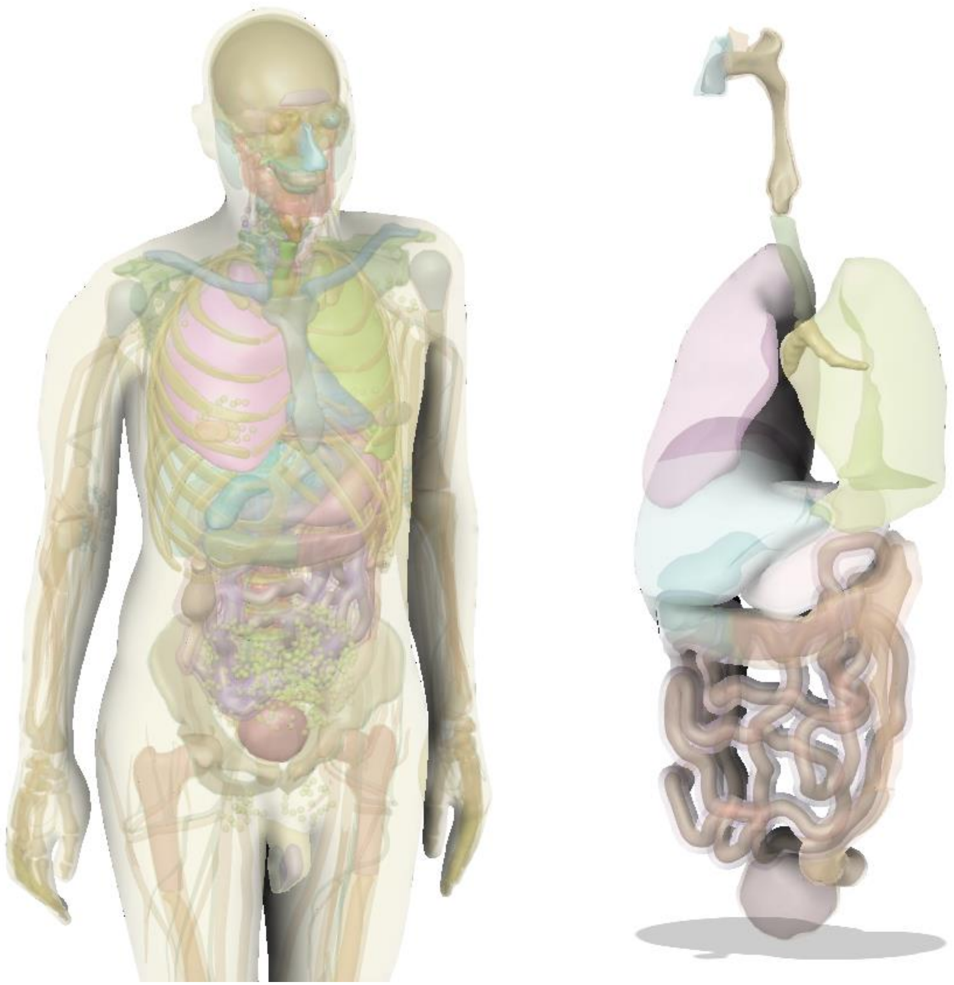


Multiphysics Modeling of Physiological Behavior: CFPD → Monte Carlo

STRONTIUM-90 ICRP VS CFPD AND PHITS MONTE-CARLO SOFTWARE

Organ	Volume [cm^3]	Dose [pGy/source]	Relative error [%]
Right Lung	1342.1	0.609	0.072
Left Lung	1123.8	1.069	0.062
Liver	1800.9	0.0074	1.10
Stomach	151.5	0.32	1.05
Bladder	39.7	2.57×10^{-3}	11.40
Small Intestine	672.9	0.0049	1.62
Ascending Colon	93.5	0.0025	6.12
Descending Colon	93.5	0.0075	4.41
Sigmoid Colon	41.6	5.59×10^{-3}	14.0
Transverse Colon	124.7	0.11	3.06

Table: Dose per unit source to the most important organs surrounding the lungs in the human body, using a I-131 as the isotope for the point sources.



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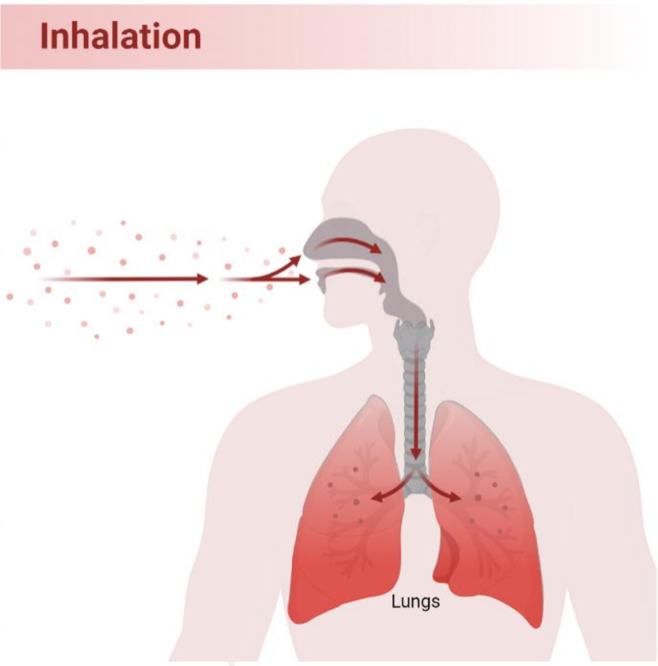
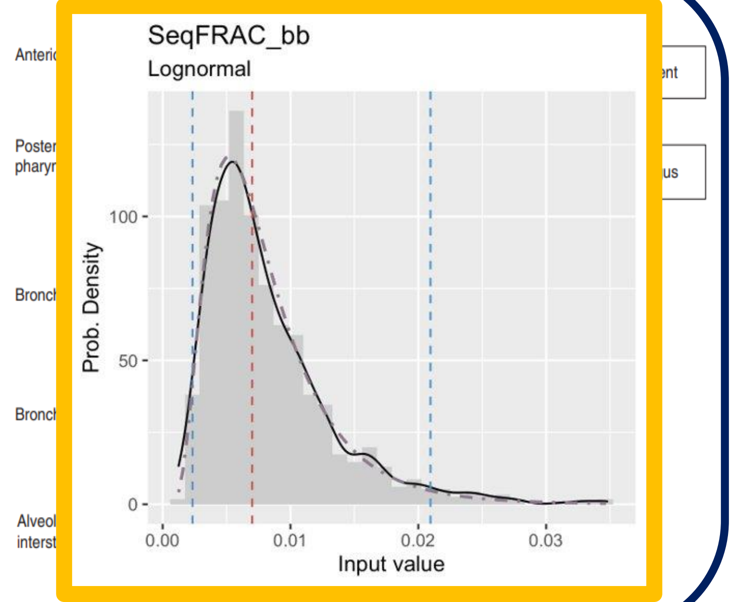
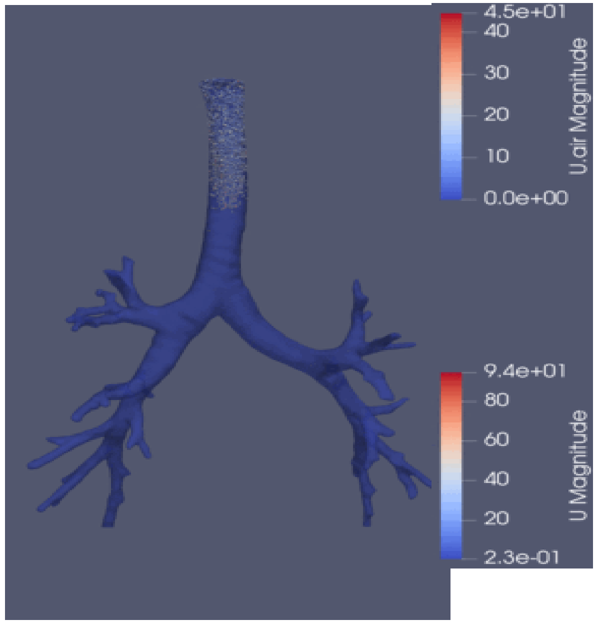
Multiphysics Modeling of Physiological Behavior: CFPD → Monte Carlo
Next Steps for Population-Specific Integration
Integration and Summary







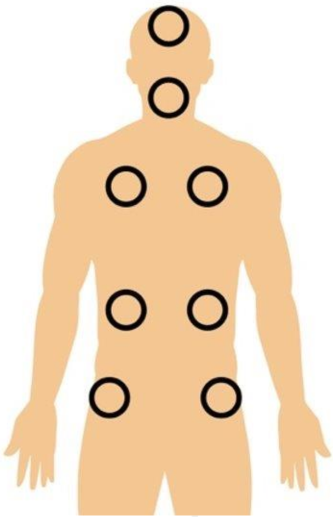
Biokinetic model: Account for particle deposition, retention, and clearance

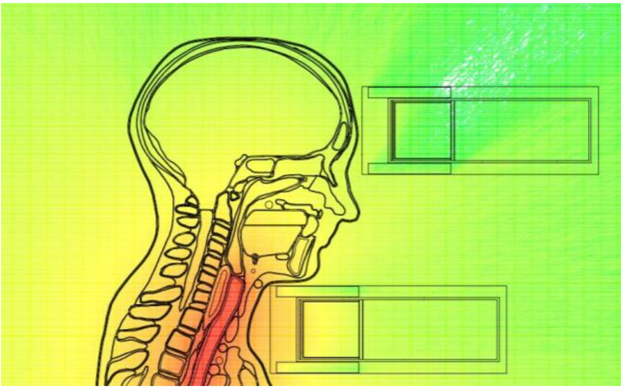
Surrogate model: Physiologically-enhanced CFPD Model

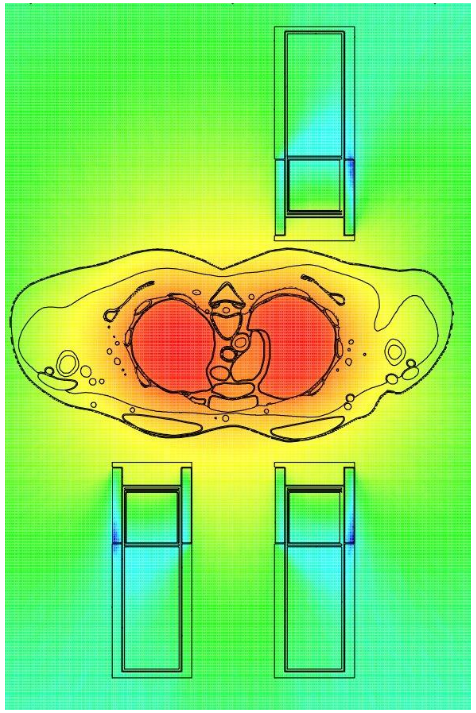
Physiologically-enhanced biokinetic model

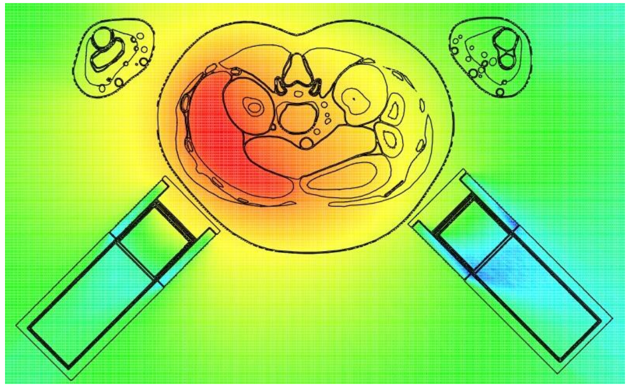
Multiphysics Modeling of Physiological Behavior: Monte Carlo → Biokinetics

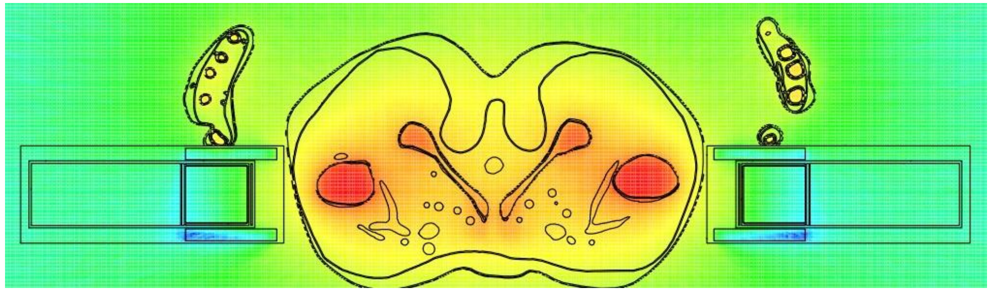
PHITS SIMULATION OF RETENTION IN SOURCE ORGANS AND DETECTOR RESPONSES



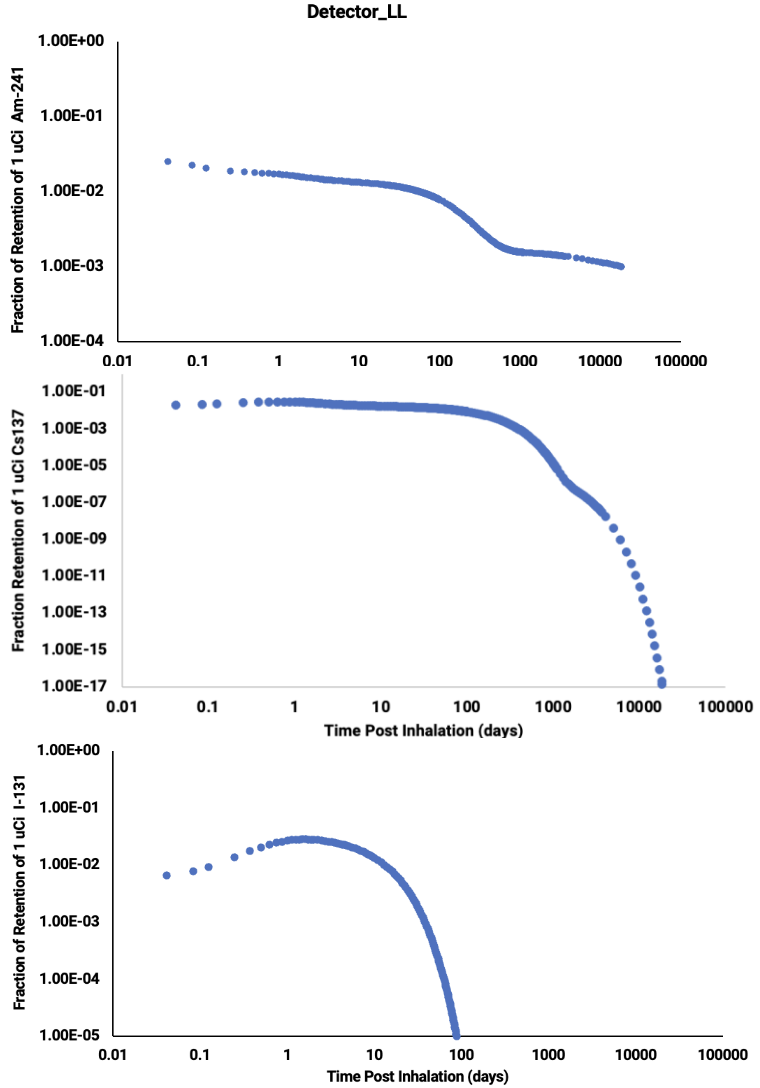








Top to Bottom: Am-241, Cs-137, I-131



Takeaways

The use of machine-learning technologies has dramatically enhanced research capabilities. Standardization of techniques has also broadened these capabilities.

By utilizing big datasets previously unattainable, researchers can now acquire deeper insights.

One example of a good study case is the human respiratory tract, due to the abundance of publicly available data and studies.

These techniques can improve mechanistic behavior of radiation in the body, complemented by radiation epidemiology, making these studies more representative. Additionally, the complexity of testing, improving, and reiterating designs, methods, and models has been significantly reduced.

RED^2 Laboratory Team at GT

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- Ignacio Bartol
- Vanessa Wei
- David Gonzalez
- Patrick Connolly
- Sherry Adadi
- Jesse Bruner
- Sergio Ruiz
- Jarred Jordan

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- Martin Graffigna (GT, Research Engineer)
- Lotem Buchbinder Shadur, Ph.D. (GT, Postdoctoral Fellow)

GT Undergraduate Research Students
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- Alejandro Martinez
- Grant Espy

Northwestern
Feinberg School of Medicine | Radiation Oncology | Woloschak Lab Grant
Alliance for Radiological Exposures and Mitigation Science

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Questions!

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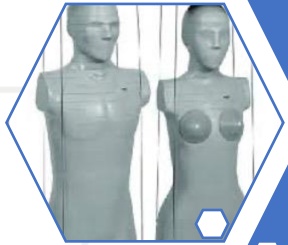


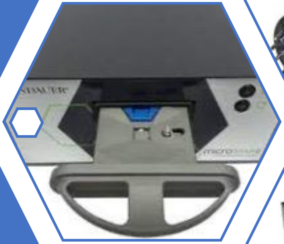
Mirion SPIR-ACE $LaBr_3$

Male CIRS Atom Phantom

Landauer microSTAR ii Medical Dosimetry System

Metallic Hemi-spheres (Be, Fe, Pb, Ta)

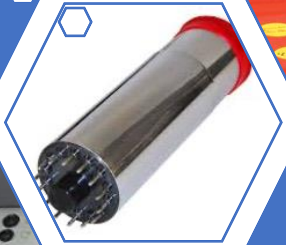
Mirion (6) 2x2 NAIS

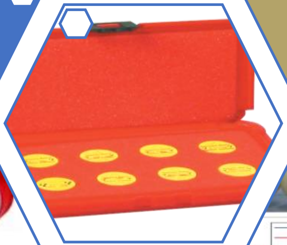


DD and DT Portable Neutron Generators

(γ/n) Sources

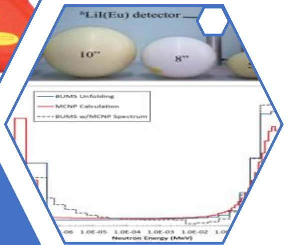
(Cf-252, 5 X 1 uCi PuBe, 51 Ci AmBe)





ADVACAM AdvaPIX Timepix3 pixelated detector

Bonner Sphere Spectro-meter System



PACE High Performan ce Computing

Supplementary Slides

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Results: Deposition Fractions

Table: Comparison of deposition values **(relative difference (RD) and absolute difference (AD))** for **polydisperse particle distribution** (5 μm AMAD) for **light exertion level (breathing rate = 1.5 $m^3 h^{-1}$) by an adult male**

Region	In-house Dep_Module	ICRP 130	RD%	AD%
ET1	0.491	0.492	-0.345	-0.170
ET2	0.264	0.265	-0.377	-0.100
BB	0.018	0.018	-1.110	-0.020
bb	0.009	0.009	-2.537	-0.023
AI	0.049	0.045	10.250	0.460
Total	0.831	0.829	0.178	0.147

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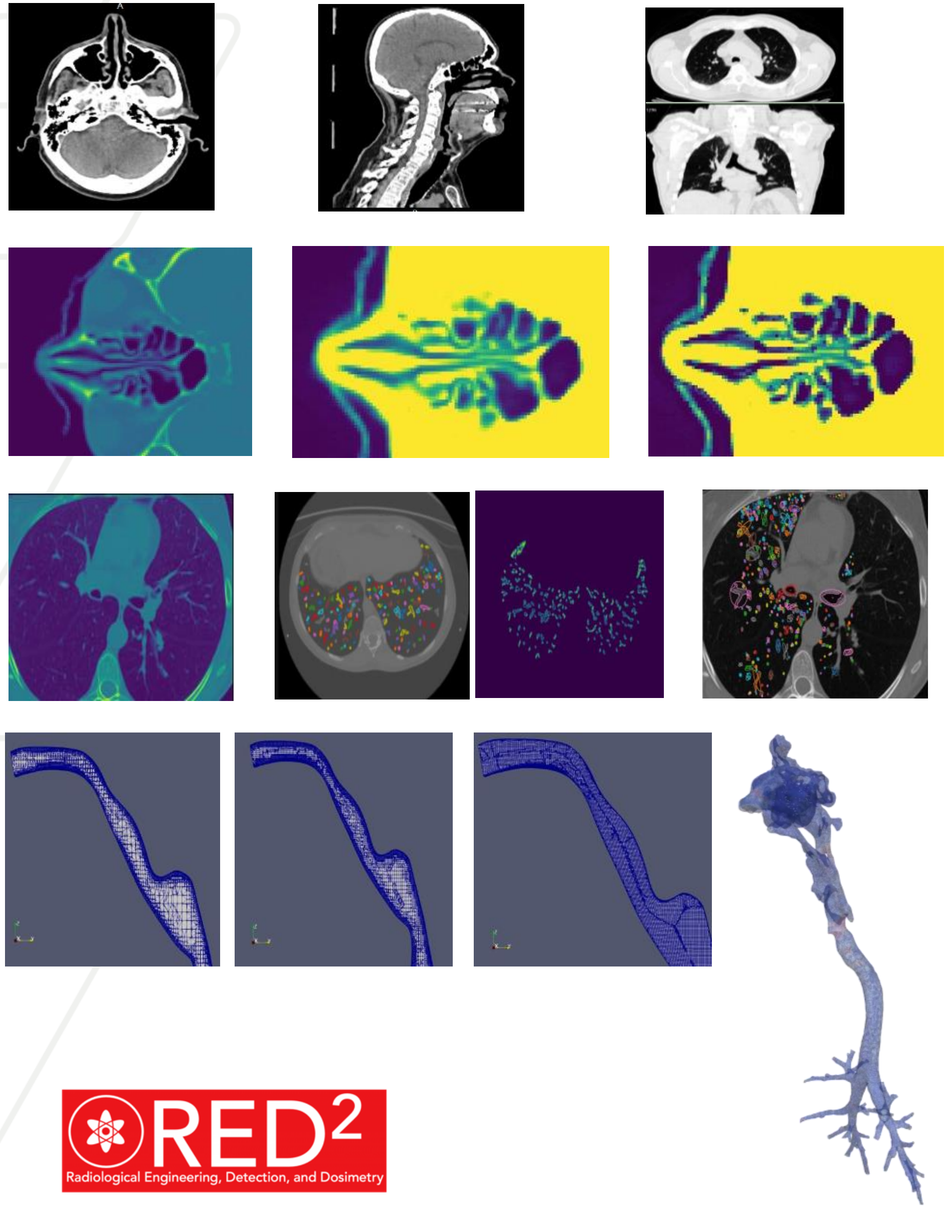
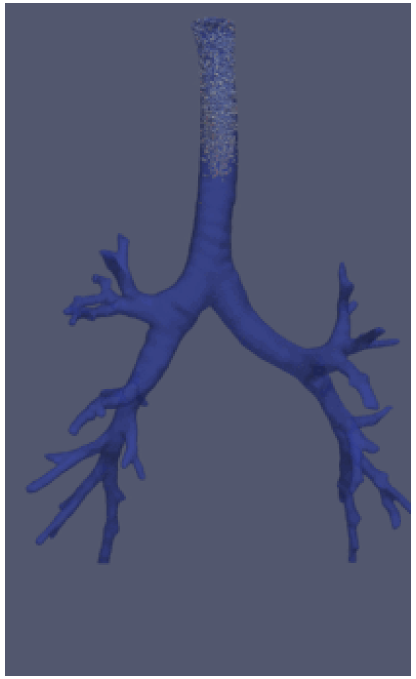
Topic 1: Aim 2 - Computational Fluid Particle Dynamics modeling of Deposition





Automated 3D CT-based algorithm of real patients (**EXACT '09 and TCIA databases**) used to reconstruct realistic HRT geometry representative of population.

- Inclusion of the nasal cavity and the paranasal sinuses (omitted in prior non-radiation studies).
- Significantly impact overall biodistribution of radionuclides body.

Reduced-order discrete element model (DEM) of the CFPD modeling the complex physics in the airways (*laminar to turbulent to irregular laminar*)

- Integrated into a Bayesian analysis of aerosol dynamics for improving HRT transfer coefficients (**Aim 1, 3**).

Sensitivity analysis will be conducted compared to ICRP's 15 generation HRTM deterministic phantom model

- Revised S-values, harnessing morphometric/ physiological data and particulate distribution (morphology, deposition velocity)
- Benchmarked with animal tomogram data of deposition from aluminosilicate particles.

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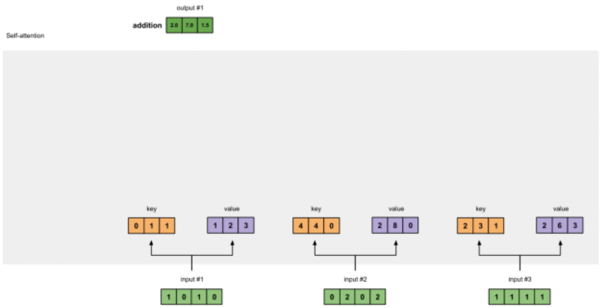
Convolutional Neural Network: Basic Operations

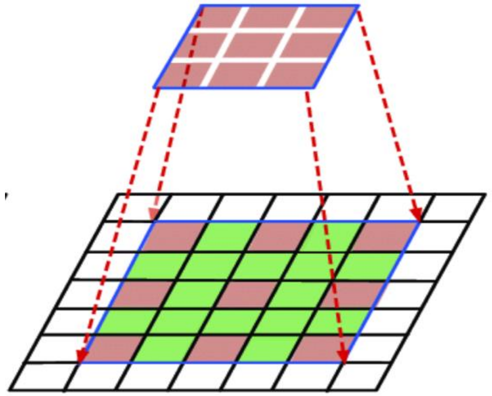
Self-attention

Provides a way to focus on different sections of data at a time

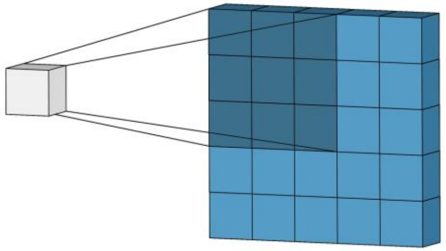


Dilated Convolution

$3\times3,\ d=2$

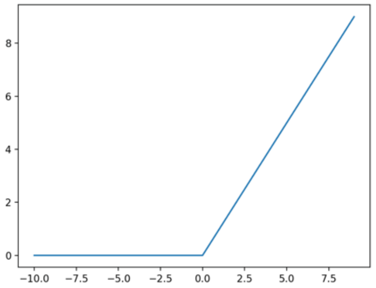


Regular Convolution



ReLU Activation Function

(positive if convolved pixel above a certain threshold)



Batch Normalization

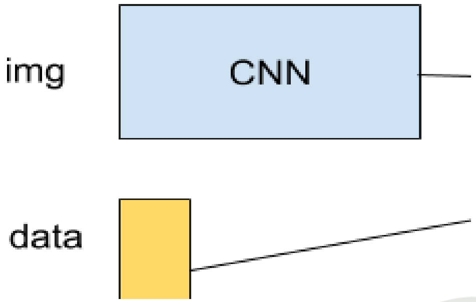
$$\mu_{batch} = \sum_{i=1}^{m} x_i \quad \textit{batch mean}$$

$$\sigma_{batch} = \sum_{i=1}^{m} \left(x_i - \mu_{batch}\right)^2 \quad \textit{batch variance}$$

$$\overline{x}_{input} = \frac{x_i - \mu_{batch}}{\sqrt{\sigma_{batch}^{2} + \varepsilon}}$$

$$y_i = \gamma \cdot \overline{x}_{input} + \beta$$

Concatenation



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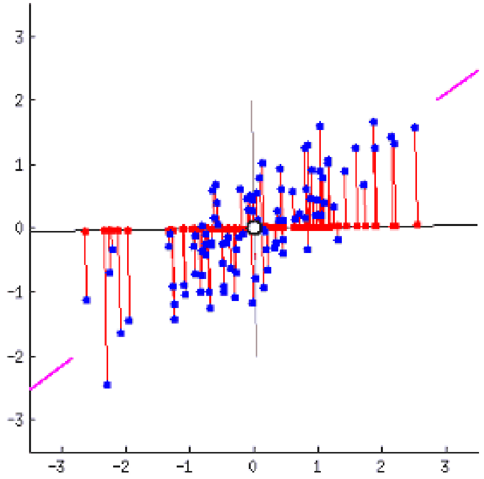
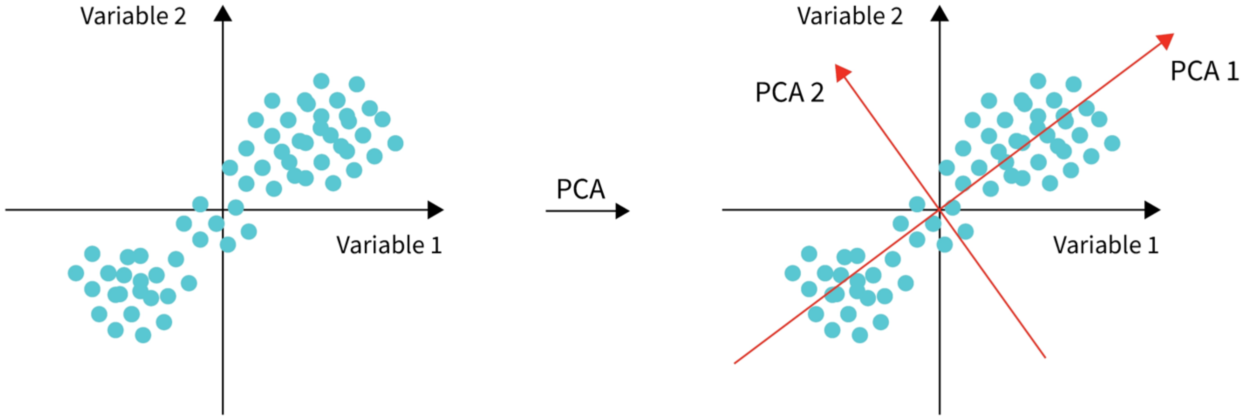
AI → CFPD → Advanced Mathematics

Singular Value Decomposition: Principal Component Analysis

Extracts the dimension or "Component" in the data with more linear variance.

Essentially, it looks for the direction in which the data is most spread

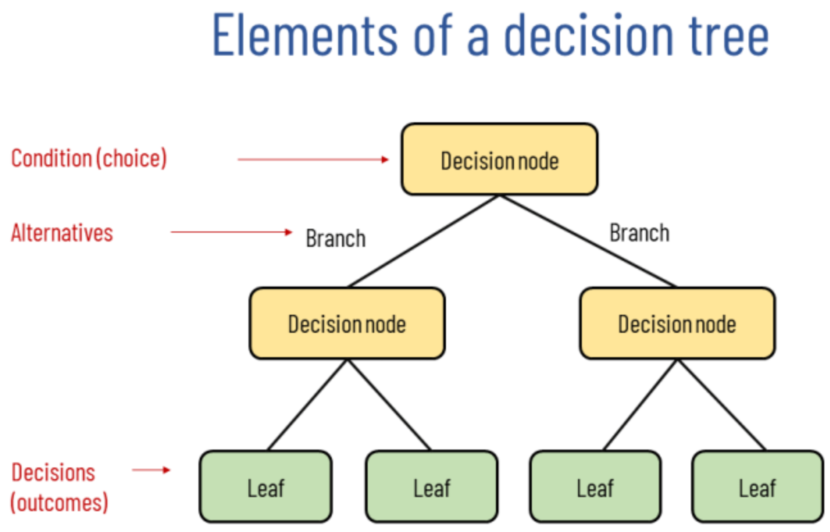


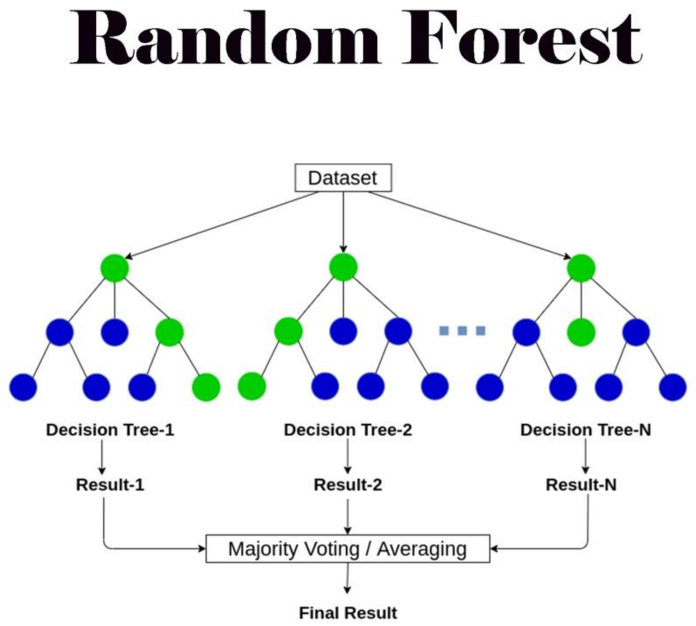


AI →CFPD → Advanced Mathematics → AI

Supervised Learning: Random Forest Regressor

- Used to evaluate the most essential features in the dataset.
- The most used variable by the decision trees to divide the branches is the feature that best describes the dataset

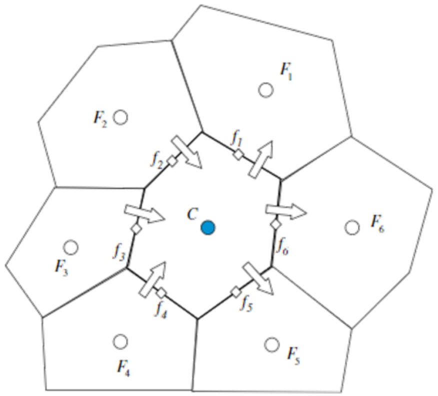




AI → CFPD
Finite Volume method - Reynold Average Navier-Stokes (RANS)

Finite Volume Method

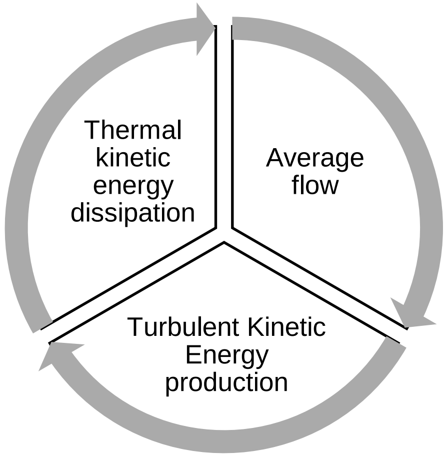
- Used to model fluid dynamics numerically.
- Preserve quantities such as energy and mass – Physically meaningful
- The exact method for average values – fewer approximations committed

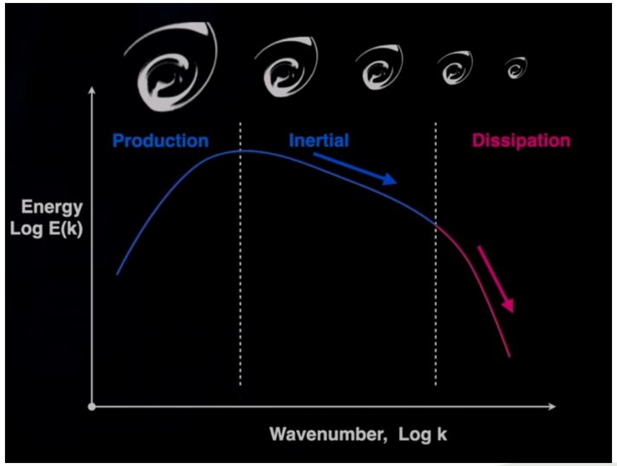


Turbulence Modeling:

Closure Equation: RANS – k-ω

- No analytical theory to predict turbulence – persists at all scales (macro/meso/micro).
- Model averages flow and treats fluctuations separately.





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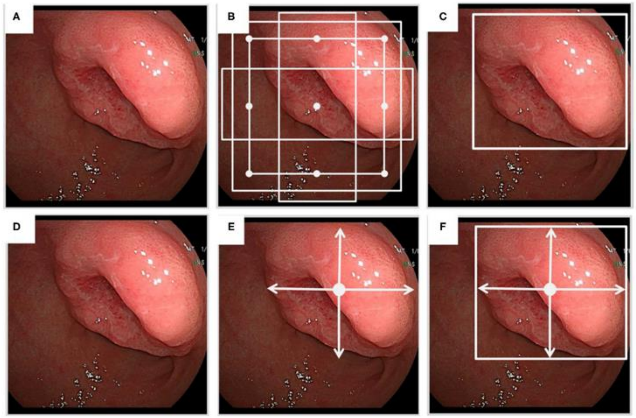
Expanding Capabilities

- **Generative Adversarial Networks** (GAN's) can model bone remodeling processes in orthopedics or dental applications. These models could **predict bone growth** or resorption patterns and assist in treatment planning for fractures, joint replacements, or dental implants.



- **Convolutional Neural Networks** (CNN's) can analyze **endoscopic images** or other GI-related data to **detect abnormalities**, such as polyps, ulcers, or lesions. These models could help in early diagnosis and treatment planning for conditions like colorectal cancer or inflammatory bowel disease.

- **Convolutional Neural Networks** (CNN's) could analyze medical images like MRIs or CT scans to detect and quantify **abnormalities in blood vessels**. This can aid in diagnosing conditions like aneurysms, vascular stenosis, or arteriovenous malformations.