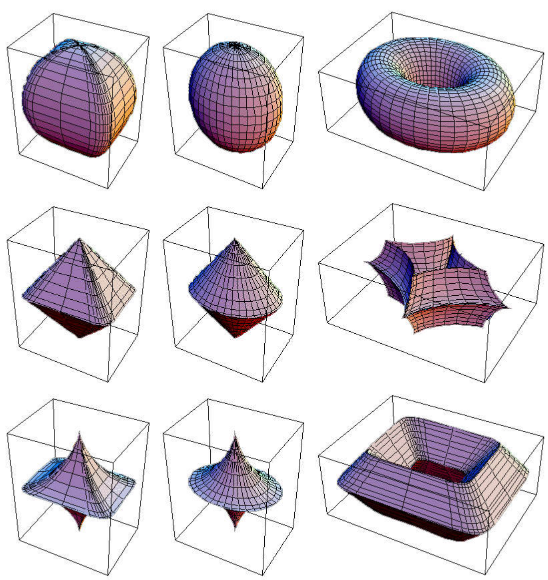
Composite Superquadric-Based Object Model for Monte Carlo Simulation of Radiological Imaging Systems

Methods: A new primitive object model is proposed for Monte Carlo simulated emission and transmission tomographic imaging systems. The object model is based upon combinations of surfaces as defined by a second-degree equation in three variables. Using rigid physically based super-quadric ellipsoids and toroids as geometric primitives, one can represent square, spherical, cylindrical, conical, and toroidal shapes with relatively simple equations. By varying the parameters of a quadric equation as well as by combining super-quadrics by means of solid boolean operators, such as union, intersection, and subtraction, a large variety of solids can be modeled with the proposed primitives to group tissues into a distinct structure.



Examples of super-quadric ellipsoids and toroids

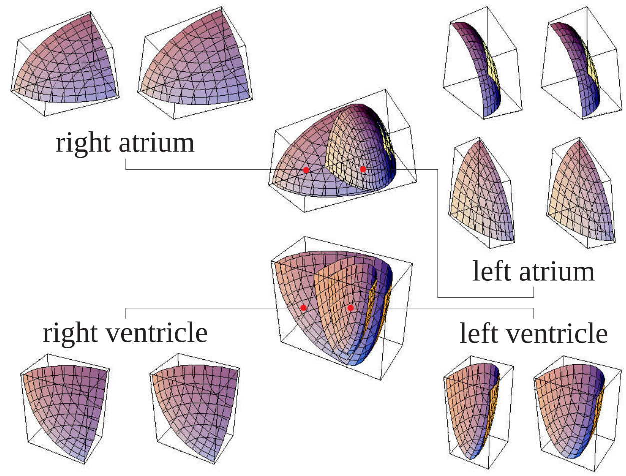
The super-ellipsoid shape is defined by

$$f_{SE} = \left(\left(\frac{x}{r_x}\right)^{2/b} + \left(\frac{y}{r_y}\right)^{2/b}\right)^{b/a} + \left(\frac{z}{r_z}\right)^{2/a},$$

and the super-toroid by

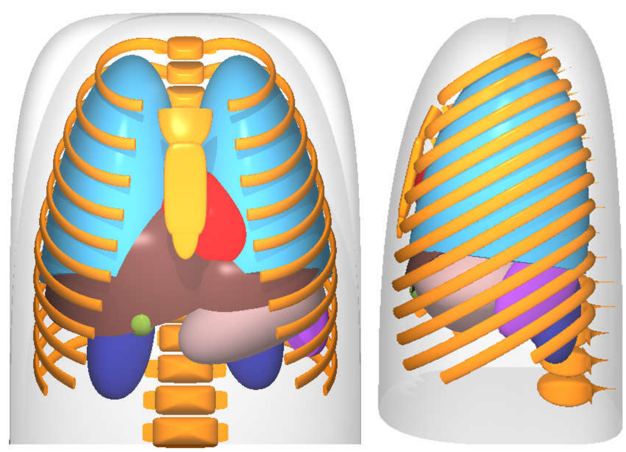
$$f_{ST} = \left|\left(\left(\frac{x}{r_x}\right)^{2/b} + \left(\frac{y}{r_y}\right)^{2/b}\right)^{b/2}\right|^{2/a} - d + \left(\frac{z}{r_z}\right)^{2/a}.$$

In principle, objects with any complexity can be modeled by a sufficient large number of primitives and appropriate primitive combinations allowing to define objects as simple as a line source but also complex anthropomorphic phantoms which can be used to facilitate clinically realistic source distributions.



Composite model of the heart

To create highly accurate phantoms, this object model can also be fused with voxelized CT or MRI data sets. In addition, a new computationally efficient algorithm to calculate the intersections of the photon path with the boundaries of the phantom primitives is proposed based on the new primitive object model. Using this object model together with a physically realistic Monte Carlo code not only generates more exact simulation results, but also facilitates SPECT simulations of clinically important and new source geometries such those encountered in dynamic cardiac SPECT imaging.



Rendered images of the superquadric-based anthropomorphic thorax phantom

The analytical phantom description of the superquadric-based phantoms is completely integrated in our Monte Carlo code in which the very same functional arguments used to design the phantom are used to calculate photon path - phantom object intersections during simulation.

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